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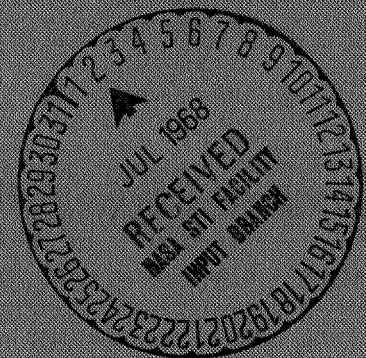
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SCREECH SUPPRESSION TECHNIQUES FOR ROCKET COMBUSTORS USING EARTH-STORABLE PROPELLANTS

by *David W. Vincent, Daniel E. Sokolowski,*
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Lewis Research Center
Cleveland, Ohio



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ABSTRACT

A rocket investigation was conducted using N_2O_4 /50 percent hydrazine 50 percent UDMH propellants to determine the effects of injector faceplate baffles, concentrated injection distribution with divergent chamber geometry, nozzle entrance length, and injector-element radial coverage. Injector faceplate baffles and concentrated propellant injections were stabilizing. No stability effect was noted by increasing the nozzle entrance length. Creation of an element void at the circumference of an injector was destabilizing.

STAR Category 33

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SUMMARY

An experimental investigation was conducted at the Lewis Research Center to determine the screech suppression effects of (1) injector faceplate baffles, (2) concentrated injection distribution with divergent chamber geometry, (3) nozzle entrance length, and (4) injector element radial coverage. The propellant combination used was nitrogen tetroxide and 50-percent hydrazine - 50 percent unsymmetrical dimethyl hydrazine (UDMH). The various screech suppression techniques were stability rated at a chamber pressure of 100 psi (689 KN/m^2) using explosive bombs. Oxidant-to-fuel mixture ratio ranged from 1.6 to 2.2.

Injector faceplate baffles were successful in suppressing screech. Increasing the velocity differential between the injectants and combustion gases by a concentrated injection distribution and divergent chamber tended to be stabilizing. No significant stability effect was noted by increasing nozzle entrance length. Injector-element radial coverage with a void at the outer circumference of the injector was destabilizing.

INTRODUCTION

Recent combustion studies at the NASA Lewis Research Center were aimed at evaluating several techniques to suppress high-frequency combustion instability in rocket thrust chambers (refs. 1 to 5). Such instability, commonly called screaming or screech, can be characterized by well-defined, high-frequency, high-amplitude pressure waves which oscillate within the thrust chamber in either longitudinal, radial, tangential, or sometimes, combined modes. Techniques to suppress screech have been studied by other researchers (refs. 6 and 7) using various propellant combinations as well as combustor sizes. However, the relative effectiveness of suppression techniques between one

propellant combination and another still remained questionable. Also, screech suppression techniques have not been fully investigated for combustors using earth-storable propellants (N_2O_4 and 50-percent hydrazine - 50-percent UDMH). Accordingly, a study was conducted with storable propellants to determine any gross differences in screech suppression from that of the hydrogen-oxygen studies conducted at Lewis (refs. 3 to 5). The effectiveness of various techniques in suppressing, primarily, the tangential mode of instability had been evaluated with hydrogen and oxygen prior to the storable program. The techniques investigated were (1) injector faceplate baffles, (2) concentrated propellant injection distribution in conjunction with divergent chamber geometry, (3) nozzle entrance length, and (4) injector-element radial coverage. The effectiveness of each suppression technique in damping screech was tested with directional explosive bombs (ref. 8).

The combustion-chamber diameter was 10.8 inches (27.4 cm), contraction ratio was 1.89, and characteristic length L^* was normally 42 inches (106.7 cm) (identical chamber as that used in the hydrogen-oxygen study). Tests were conducted at a nominal chamber pressure of 100 psia (689 KN/m^2), a thrust of 6700 pounds (29.8 KN), and at mixture ratios from 1.6 to 2.2.

APPARATUS

Facility

Tests were conducted in a Lewis altitude test facility. Test objectives did not require an altitude capability, but it was used to handle the toxic exhaust gases and any propellant spills that might occur. A photograph of a typical combustor installed in the test cell is shown in figure 1. The propellant temperatures were maintained at $65^\circ \pm 11^\circ \text{F}$ ($292^\circ \pm 262^\circ \text{K}$) and no attempt was made to reduce this temperature variation. The facility was equipped with pressure-regulated propellant feed systems.

Combustor Descriptions

Heat-sink hardware was used in all tests. The combustors consisted of an injector, chamber, and convergent-divergent nozzle with a nominal throat area of 48 square inches (31 cm^2). The nozzle contraction ratio was 1.9, and the expansion ratio was 1.3 throughout the testing. This expansion ratio nozzle was used because test objectives did not require a large area ratio and nozzle losses were more accurately predictable. A bomb ring was also incorporated into the various configurations for stability rating. The four ports were tangential to a 8.8-inch (22.4-cm) circle, that is, 2 inches (3.08 cm) smaller than the chamber. All inside surfaces of the mild steel combustors (except injectors)

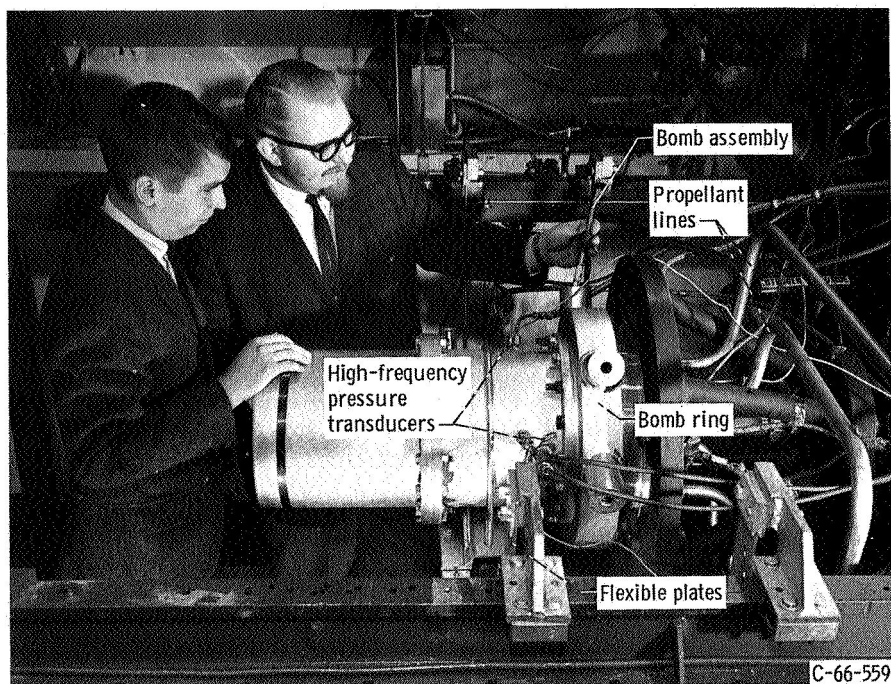


Figure 1. - Test cell with engine installed.

were coated with 0.012 inch (0.31 mm) of a nickel-base alloy and 0.018 inch (0.48 mm) of zirconium oxide. All injectors tested were flat-faced, fuel-oxidant-fuel triplets with 60° , 0.5-inch (1.3-cm) impingement. Momentum ratios (momentum oxidant/momentum fuel) were calculated for a mixture ratio range of 1.6 to 2.20. Further description of each test configuration is presented in the subsections immediately following.

Injector faceplate baffles. - Sketches of the experimental baffle configurations tested with storable propellants are presented in table I. (For comparison, table II lists the configurations tested in the hydrogen-oxygen investigation.) The number of baffle compartments was varied from 3 to 20 and blade axial lengths from 0.75 to 4.5 inches (1.9 to 11.5 cm). A 10.8-inch (27.4-cm) diameter, 100-element triplet injector with a flat face was used in all baffle tests. The injector orifice specifications were as follows: oxidant orifice diameter, 0.091 inch (0.23 mm); fuel orifice diameter, 0.054 inch (0.14 mm); momentum ratio range tested, 1.14 to 2.12. The injector pattern had 10 pie-shaped sectors each containing 10 elements. A 0.5-inch (1.3-cm) gap between sectors permitted various baffle configurations to be tested without altering injection pattern. The baffles were bolted to the injector at the center and at the periphery by a ring welded to the blades. Therefore, a slight gap would form between the injector and blades during testing. The nickel-base alloy and zirconium oxide coating was also applied to the 3/16-inch (0.48-cm) thick mild steel baffles which allowed 3- to 4-second runs without damage. A typical arrangement with the injector, 10-compartment baffle, and bomb ring is

TABLE I. - STORABLE-PROPELLANT BAFFLE CONFIGURATIONS TESTED

[Solid squares represent configurations tested.]

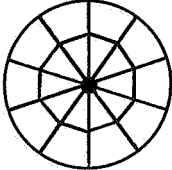
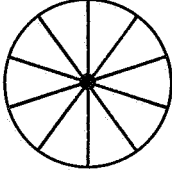
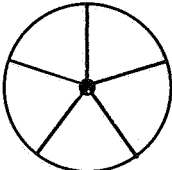
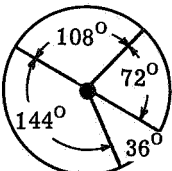
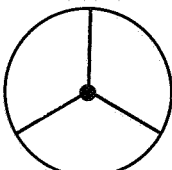




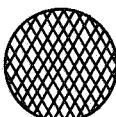
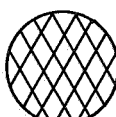

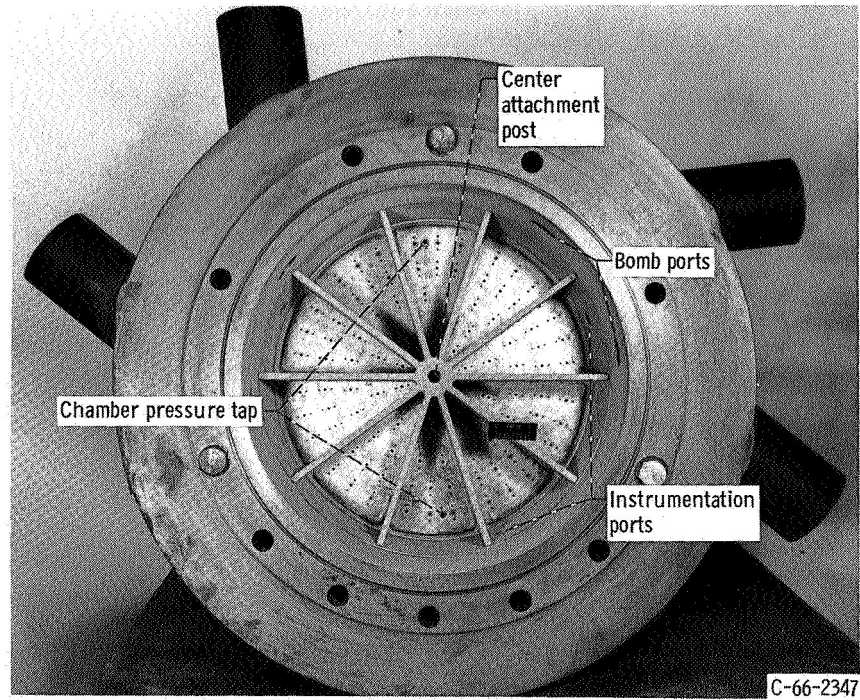
Baffle configuration		Axial length, in. (cm)				
		4.5 (11.5)	3.5 (8.9)	1.5 (3.8)	1.0 (2.5)	0.75 (1.9)
	20 Compart- ments					
	10 Radial blades					
	5 Radial blades					
	4 Radial blades					
	3 Radial blades					

TABLE II. - HYDROGEN-OXYGEN BAFFLE CONFIGURATIONS TESTED^a

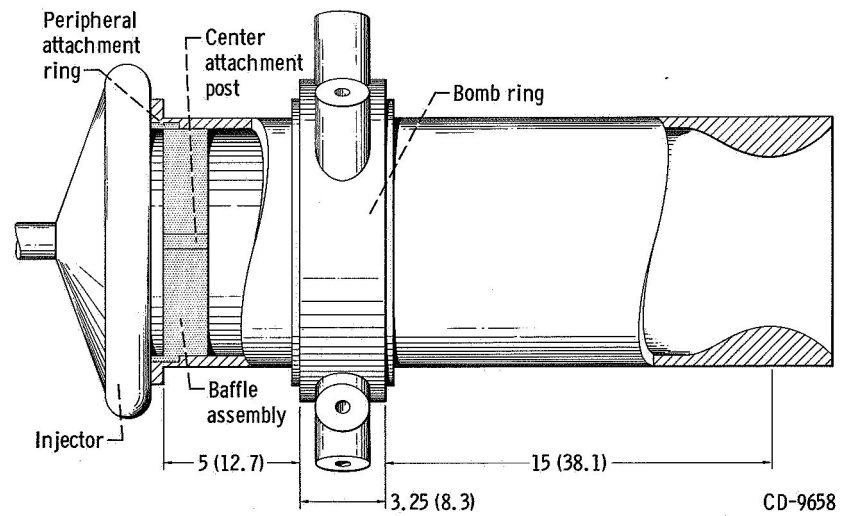
[Solid squares represent configurations tested.]

Baffle configuration		Axial length, in. (cm)					
		2 (5.1)	1.66 (4.2)	1.25 (3.2)	1 (2.5)	0.75 (1.9)	0.50 (1.3)
	7 Radial blades						
	4 Radial blades						
	3 Radial blades						
	Extended triangle						
	100 Compartment						
	25 Compartment						
	7 Compartment						

^aSee ref. 3.

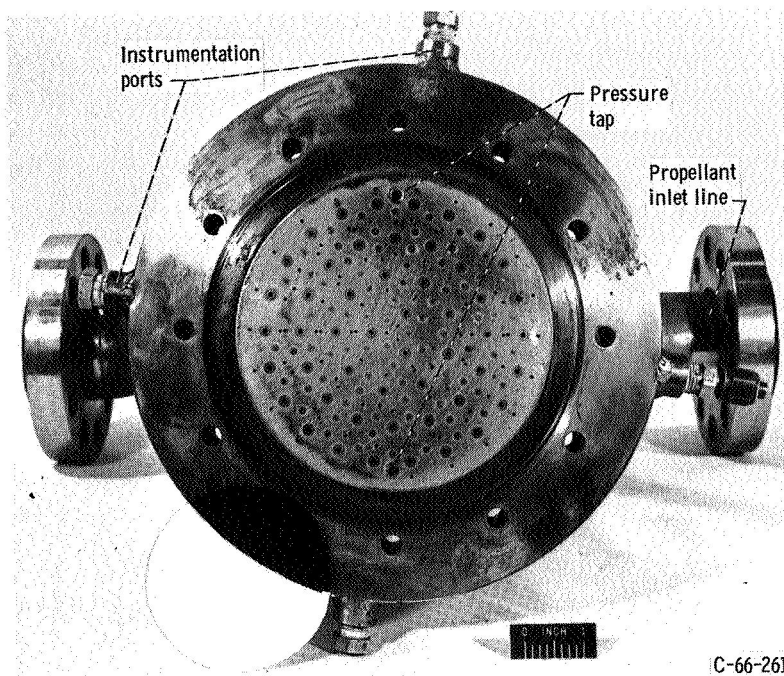


(a) Ten-blade radial baffle assembled with injector and bomb ring.



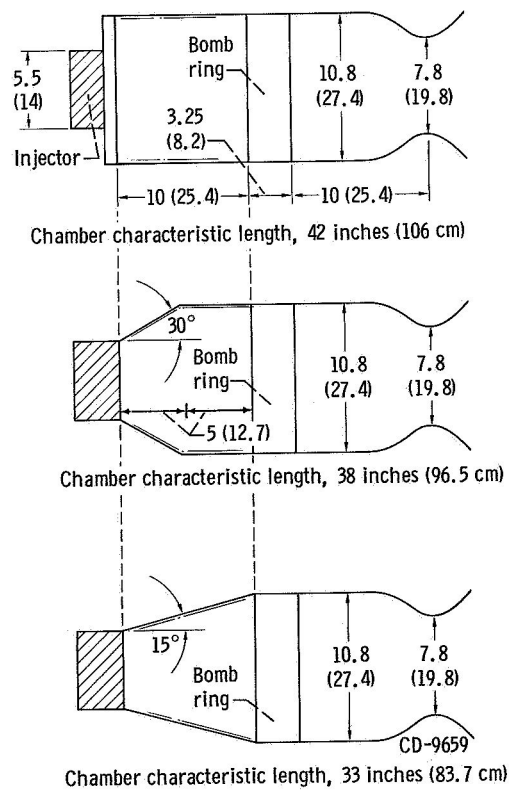
(b) Side view cutaway of typical baffle test combustor. (All dimensions are in inches (cm).)

Figure 2. - Baffle test combustor.



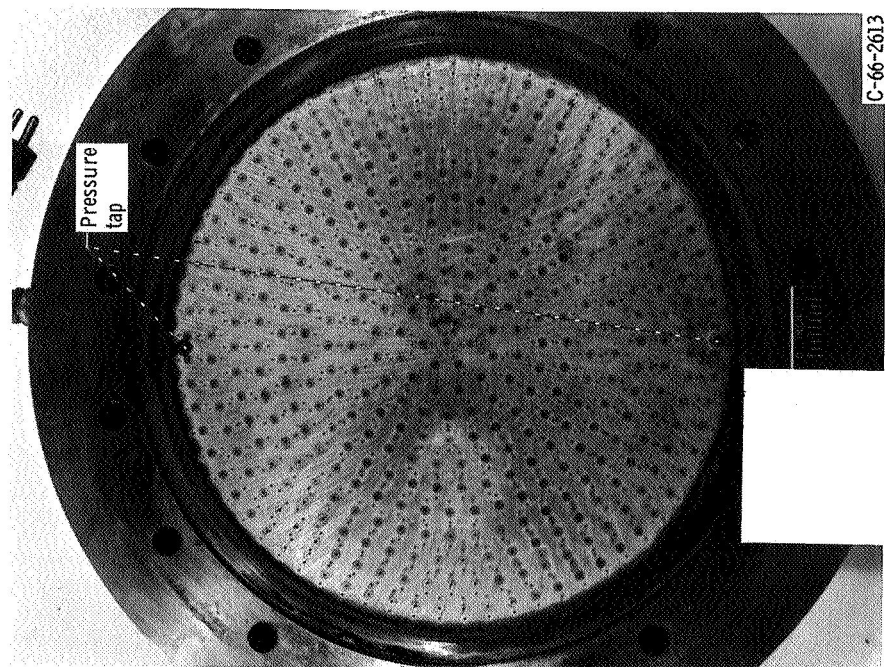
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(a) Fifty-element fuel-oxidant-fuel triplet injector. Injector diameter, 5.5 inches (14 cm); oxidant orifice diameter, 0.081 inch (0.21 mm); fuel orifice diameter, 0.0469 inch (0.12 mm); impingement distance, 0.5 inch (1.3 cm); impingement angle, 60° .

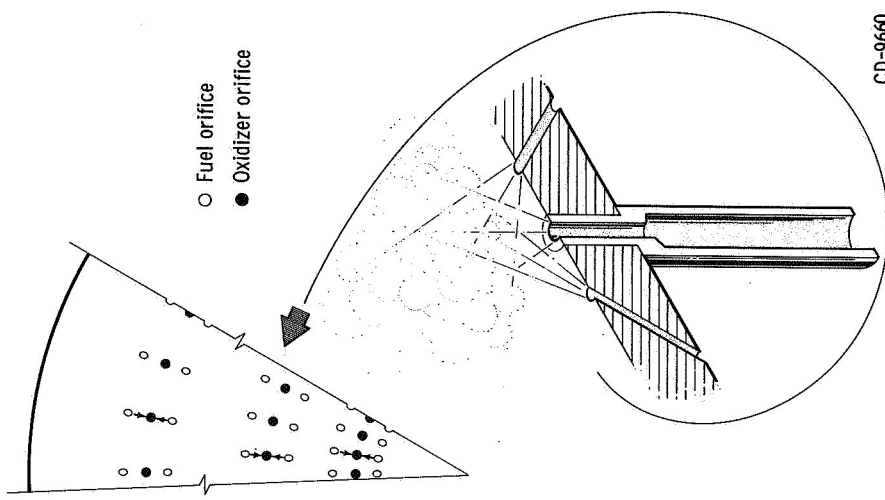


(b) Chamber configurations. Injector to nozzle contraction ratio, 0.49; chamber to nozzle contraction ratio, 1.9. (All dimensions are in inches (cm).)

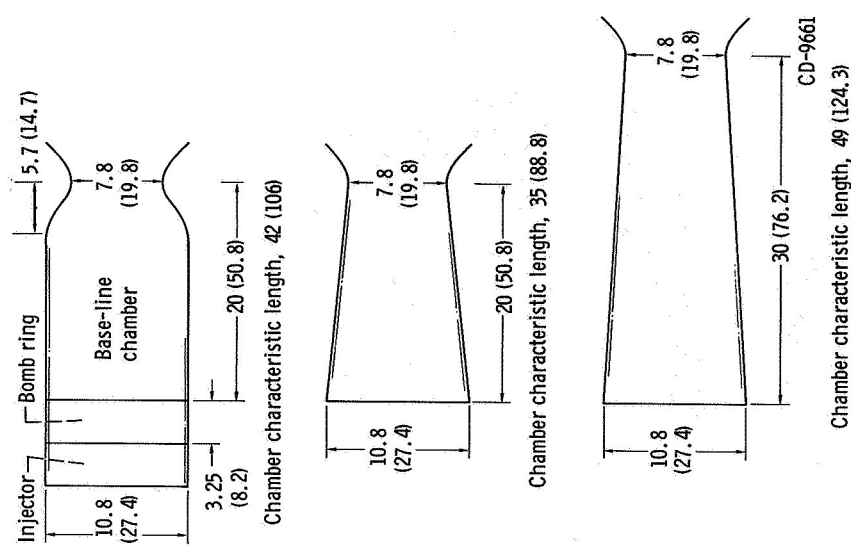
Figure 3. - Combustor configurations of concentrated injection distribution investigation.



(a) 401-Element fuel-oxidant-fuel triplet injector. Fuel orifice diameter, 0.027 inch (0.07 mm); oxidant orifice diameter, 0.045 inch (0.11 mm); impingement distance, 0.5 inch (1.3 cm); impingement angle, 60°.



(b) Ninety-element fuel-oxidant-fuel triplet injector showing element pattern. Oxidant orifice diameter, 0.078 inch (0.2 mm); fuel orifice diameter, 0.052 inch (0.13 mm); impingement angle, 60°.



(c) Tapered (converging) chambers tested with 90- and 401-element injectors. (All dimensions are in inches (cm).)

Figure 4. - Combustor configurations of nozzle entrance length investigation.

shown in figure 2(a). The bomb-ring position was held constant at 5 inches (12.7 cm) from the injector face so that different axial blade lengths could be evaluated under the same test conditions.

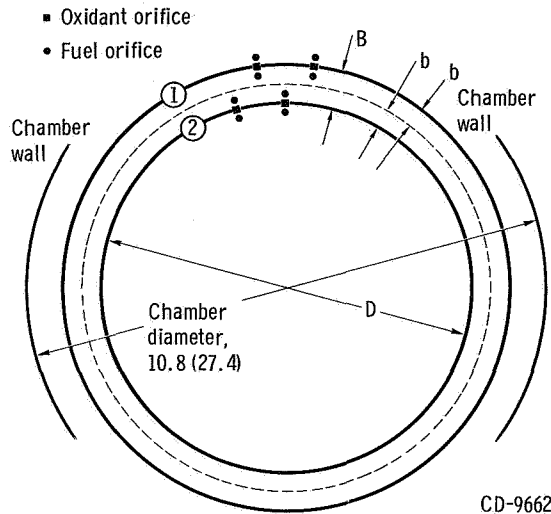
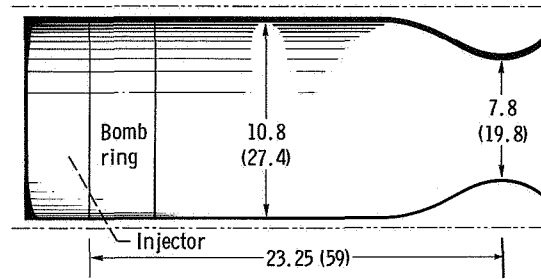
Concentrated injector distribution with divergent chamber geometry. - Sketches of the storable combustor configurations used in the injector concentration portion of the study are presented in figure 3. A 50-element triplet injector with a 5.5-inch (14-cm) diameter was used in all tests (fig. 3). The injector orifice specifications are as follows: oxidant orifice diameter, 0.081 inch (0.21 mm); fuel orifice diameter, 0.0469 inch (0.12 mm); momentum ratio range tested, 1.06 to 2.02. With the bomb ring positioned 10 inches (25.4 cm) from the injector, the chamber geometries evaluated were (1) the 10.8-inch (27.4-cm) cylinder, (2) the 30° taper, and (3) the 15° taper.

Nozzle entrance length. - Tapered (converging toward the nozzle) chambers were evaluated with two injector designs as shown in figures 4(a) and (b). One injector had 401 elements, while the other had 90. The orifice specifications of the 401-element injector are as follows: oxidant orifice diameter, 0.027 inch (0.07 mm); fuel orifice diameter, 0.045 inch (0.11 mm); momentum ratio range, 1.10 to 2.12. The specifications of the 90-element injector are as follows: oxidant orifice diameter, 0.078 inch (0.2 mm); fuel orifice diameter, 0.052 inch (0.13 mm); momentum ratio range tested, 1.44 to 2.68. With the bomb ring located next to the injector, the chamber geometries evaluated were (1) the 20-inch (50.8-cm) cylinder, (2) the 20-inch (50.8-cm) taper, and (3) the 30-inch (76-cm) taper. Sketches of typical configurations are presented in figure 4(c).

Injector element radial coverage. - The storable propellant element coverage tests were conducted using a modification of the 401-element injector which is shown in figure 4(a). By welding shut the outer row of elements, the original injector was changed from 90 to 70 percent coverage of the face area as shown in figure 5. Tests were conducted with the bomb ring next to the injector in all tests.

Instrumentation

The combustor and facility were instrumented to record and monitor the normal operating parameters. Included were propellant-tank pressures and temperatures, propellant flow rates, injection pressures and temperatures, combustion-chamber pressure, combustor thrust, and ambient conditions. Pressure measurements were obtained by the use of strain-gage transducers, and temperatures were measured by iron-constantan thermocouples. Water calibrated, $1\frac{1}{2}$ -inch (3.8-cm) turbine flowmeters measured mass flow rates. Pressure and temperature measurements at the flowmeters were used to calculate the fluid densities. Thrust was measured with a double bridge, strain-gage load cell in compression. The instrumentation calibrations were electrically checked



Definition of effective area with row 1 welded closed

$$\text{Effective area} \equiv \frac{\pi}{4} (D + B)^2 \quad \text{where} \quad \frac{B}{2} = b$$

$$\text{Percent coverage} \equiv \frac{\frac{\pi}{4} (D + B)^2}{\frac{\pi}{4} (10.77)^2} = \frac{(D + B)^2}{(10.77)^2}$$

Figure 5. - Combustor used during injector element radial coverage test and sketch defining coverage. (All dimensions are in inches (cm).)

prior to each test. The maximum probable error in combustion performance caused by measurement errors was determined to be about ± 1 percent.

Pressure oscillations within the combustion chamber were monitored for frequency and amplitude by high-frequency piezoelectric pressure transducers. These transducers (usually three) were mounted in water-cooled jackets flush to the chamber wall and had an overall system frequency response that was flat to 6000 hertz. With the bomb ring located other than adjacent to the injector, the transducers were located nominally at 3 and 7 inches (7.6 and 17.8 cm) (± 1 in. (2.54 cm)) from the injector. An additional pickup was located 3 inches (7.6 cm) from the injector but was rotated clockwise 135° from the others. With the bomb ring located at the injector, the dimensions would be increased by about 3.25 inches (8.2 cm). Modes of instability were identified from both frequency and phase-angle measurements between the transducers.

Measured operating parameters were recorded on both a galvanometric oscillograph and a high-speed digital recorder for computer processing. Data from the high-frequency pressure transducers as well as bomb initiation markers and a time code were recorded on FM magnetic tape.

PROCEDURE

The various combustor configurations were tested at a nominal chamber pressure of 100 psia (689 kN/m^2) and over a mixture ratio O/F range of 1.6 to 2.2. Figure 6 shows oscillograph traces of combustor parameters recorded during a typical test. About 2 seconds were required for the combustor to achieve steady-state conditions. The heat-sink hardware allowed about 3 seconds total run time without damage. An electronic controller regulated the propellant flow rates (and maintained constant chamber pressure and mixture ratio). Program timers sequenced propellant valves and bomb initiation.

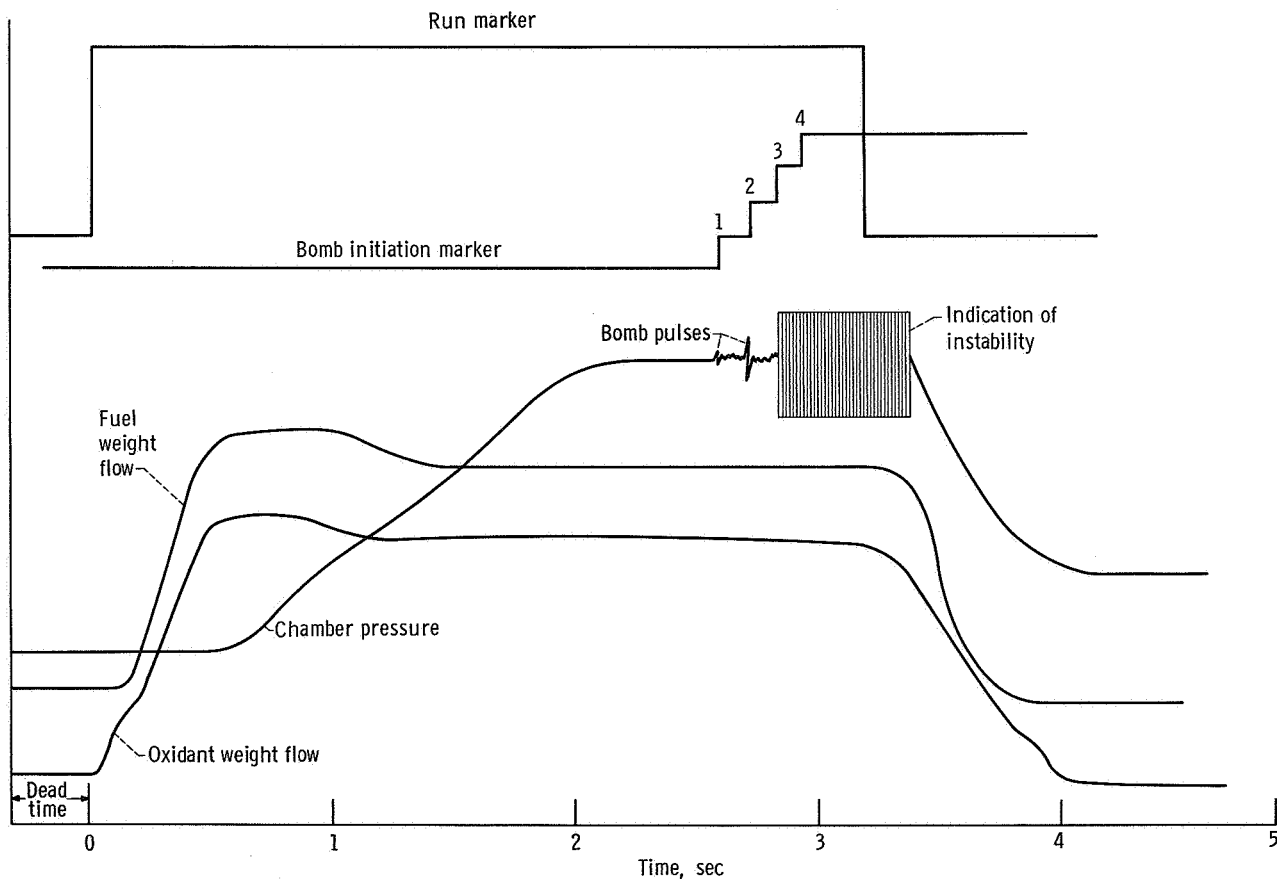


Figure 6. - Oscillograph trace of typical combustor test showing bomb rating technique used.

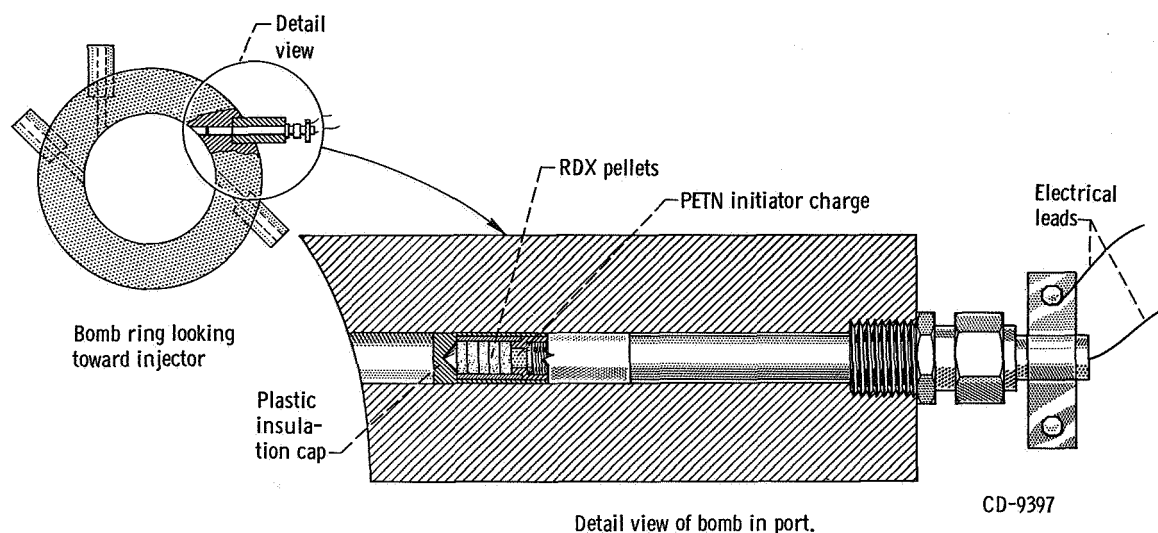


Figure 7. - Bomb ring and RDX explosive bomb used for stability rating.

The stability rating method used with storable propellants was to detonate RDX explosive charges in a bomb ring (fig. 7) to induce combustion instability. The charge initiator consisted of 1.63 grains (0.105 g) of PETN and an exploding bridgewire. Therefore, on stability plots, the 1.63-grain (0.105-g) charge is PETN only and the larger charges all contain 1.63 grains (0.105 g) of PETN. Further description of the bomb and explosive can be found in reference 8. The four bombs were detonated electrically at approximately 100-millisecond intervals during the steady-state period of combustor operation. The bombs were usually successively larger in size (i. e., contained more RDX). The 100-millisecond interval allowed ample time for each pulse to damp before initiation of the following charge. The pulse which initiated screech was determined by analysis of the flush-mounted high-frequency transducer output.

The heat-sink bomb ring was located as close as possible to the injector consistent with the constraints imposed by the specific tests being conducted. For individual test location, see figures 2(b), 3(b), 4(c), and 5. The explosive was in pellet form and the length of the initiator sleeve and bomb port limited the maximum charge size to 41 grains.

RESULTS AND DISCUSSION

Injector face baffles, chamber geometry, and injector configuration effects were investigated and are discussed herein. Previously, similar tests were conducted at Lewis using a hydrogen-oxygen propellant combination. The storable propellant tests of this report were to study gross effects of propellant variation on screech suppression. The

chamber size was identical for both investigations, but, because the methods of rating and chamber pressure were different, only qualitative comparison were possible.

For this study, the detonation of directional explosive charges produced pressure perturbations which would either damp or initiate instability. The rating parameter used for the stability analysis was bomb size because of the data scatter encountered in using pressure pulse amplitude data (refs. 1 and 10). Nominal chamber pressure was 100 psia (689 kN/m^2) and mixture ratios O/F normally ranged between 1.6 and 2.2.

Evaluations of the suppression techniques are presented in the following order:

- (1) Injector faceplate baffle effects
- (2) Concentrated propellant injection distribution and divergent chamber geometry effects
- (3) Nozzle entrance length effects
- (4) Injector element radial coverage effects

Injector Faceplate Baffle Effects

Baffles on an injector faceplate effectively suppressed screech for a hydrogen-oxygen propellant combination (ref. 3) and with earth-storable propellants (refs. 11 and 12). Various mechanisms to explain the observed effectiveness were suggested, such as, compartmentalization of combustion, acoustic damping, reduction of cross velocity, or acoustic interference. Although no controlling mechanism was isolated, a relation was found (ref. 3) between axial blade length and maximum compartment dimension required for screech suppression. Accordingly, the storable-propellant tests of this investigation were designed to investigate this relation and any gross differences a different propellant combination might produce.

Baffle compartments were varied in number from 3 to 20 (table I) and blade axial lengths from 0.75 to 4.5 inches (1.9 to 11.5 cm). Rating was based on the maximum charge size which was damped by the baffles or the minimum charge which induced instability. Because the rating technique was limited by the maximum charge of 41 grains (2.66 g) of RDX, some baffle configurations could not be pulsed unstable.

A stability map for the unbaffled combustor (shown in fig. 2(a) with baffle) is presented in figure 8(a). The combustor was spontaneously unstable from ignition (zero bomb size) for mixture ratios from 1.60 to about 1.94, although 6 grains (0.39 g) of RDX induced instability for mixture ratios from 2.06 to 2.35. The predominant mode of instability was the first tangential (2450 Hz) during both spontaneous and induced instability (fig. 8(b)). The 4900-hertz frequency (possibly the first-radial mode) is suspected to be a Fourier harmonic produced by the spectral analyzer. Chugging (280 Hz) was noted for some tests at mixture ratios above 2.0.

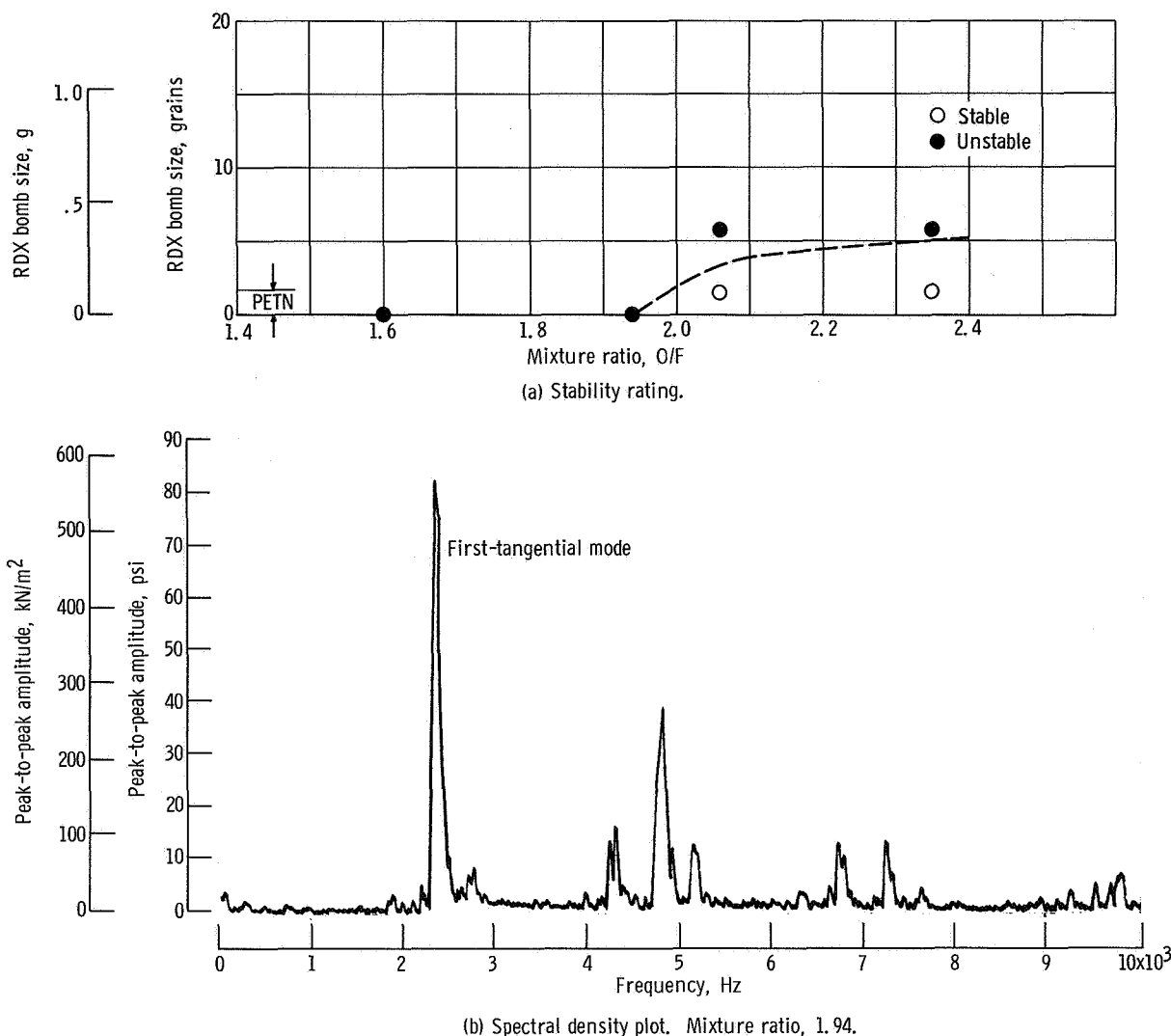
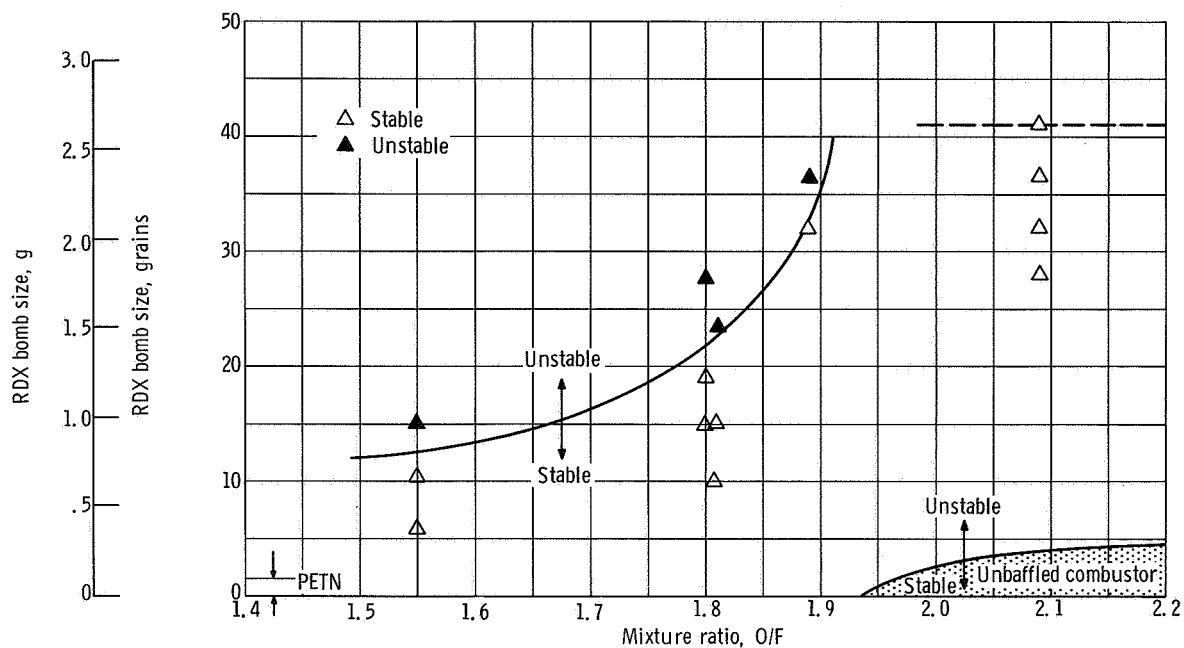


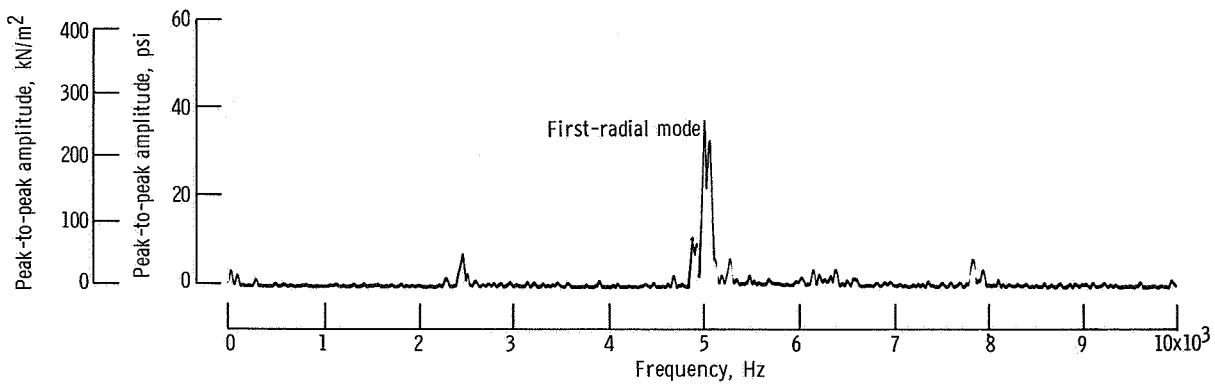
Figure 8. - Basic combustor stability characteristics (injector face plate baffle investigation).

Results of the individual baffle tests are presented in the order of increasing number of baffle compartments. Rather than use discrete bomb sizes, curves were faired through the boundary between screech inducing bomb sizes and those which did not induce screech. This is due to the large gradations between bomb sizes. The faired stability boundaries will be used in the discussion. It was noted that stability was maximum (i.e., stable to 41 grains (2.66 g)) at a mixture ratio of about 2.0 and above for all configurations, but chugging also occurred at this point and the amplitude increased with increasing mixture ratio. Therefore, this discussion will be concerned primarily with the stability between mixture ratios of 1.5 to 2.0 which is the range normally used in vehicle application of these propellants.

Only a 1.5-inch (3.8-cm) axial length was tested with the three-blade configuration. The stability provided by this baffle was a significant improvement over the unbaffled

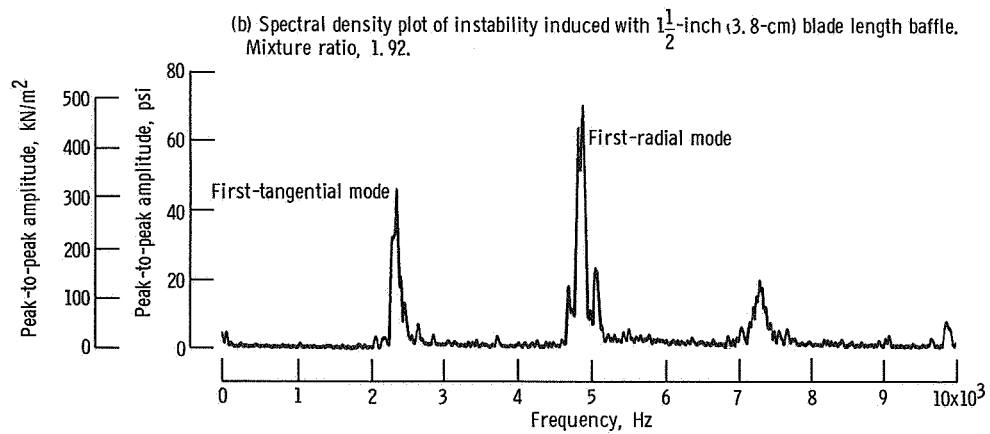
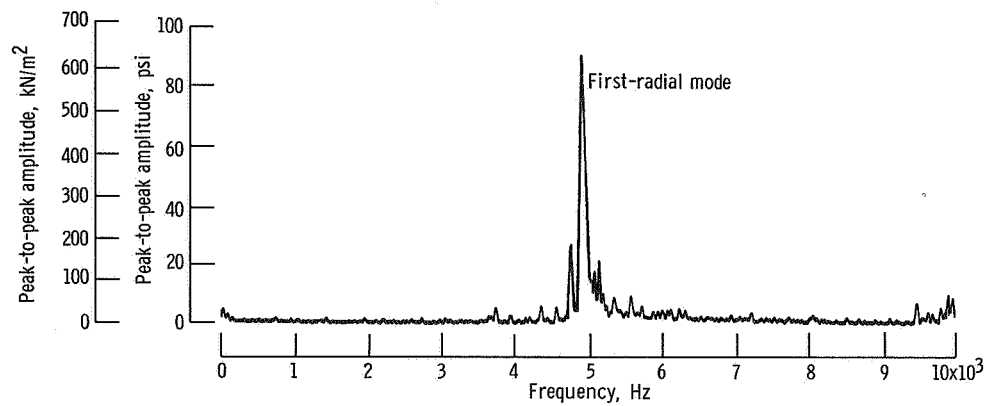
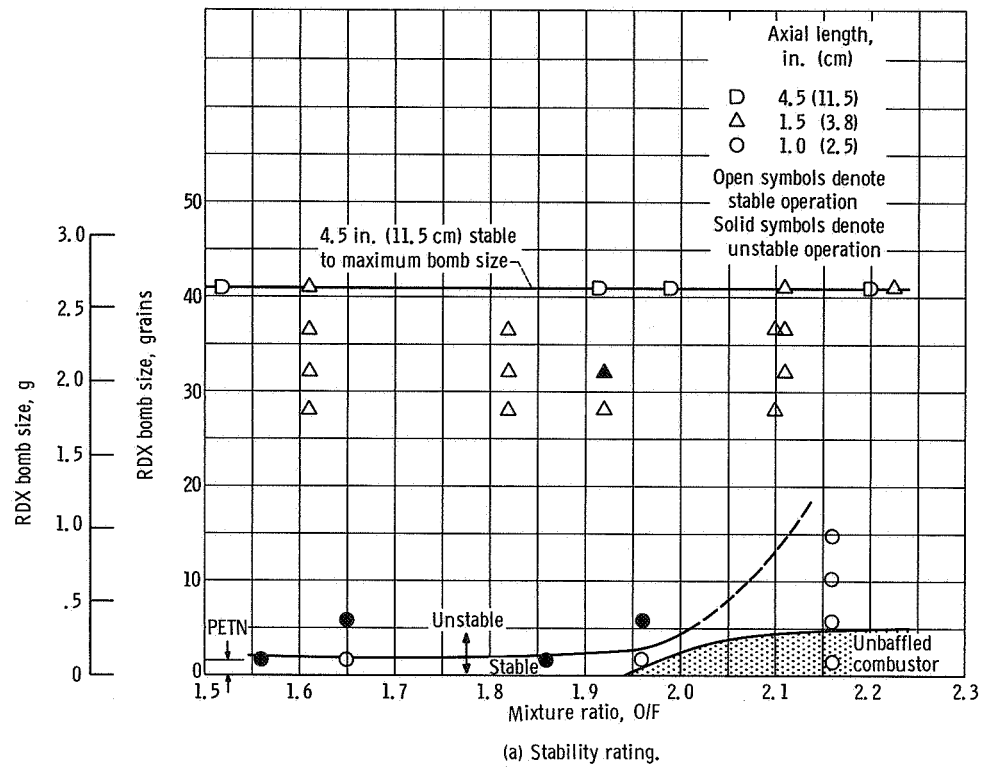


(a) Stability rating of 1.5-inch (3.8-cm) blade.



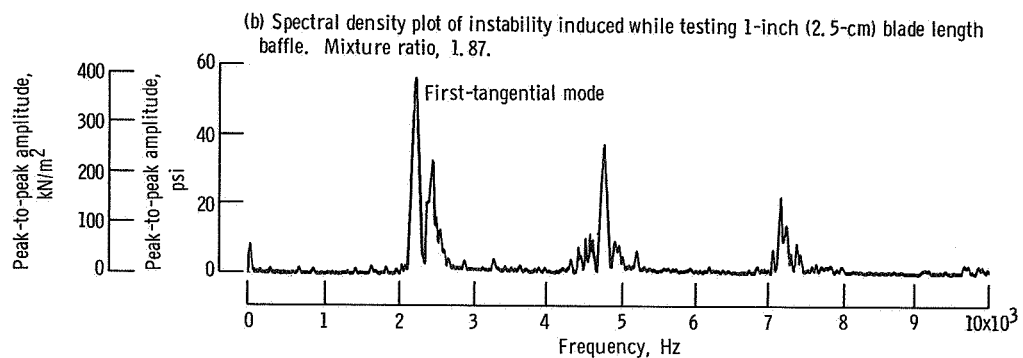
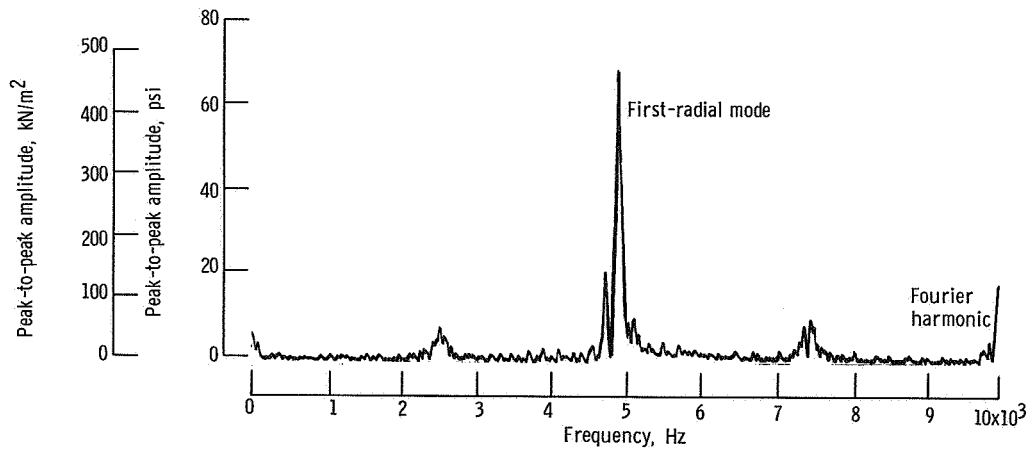
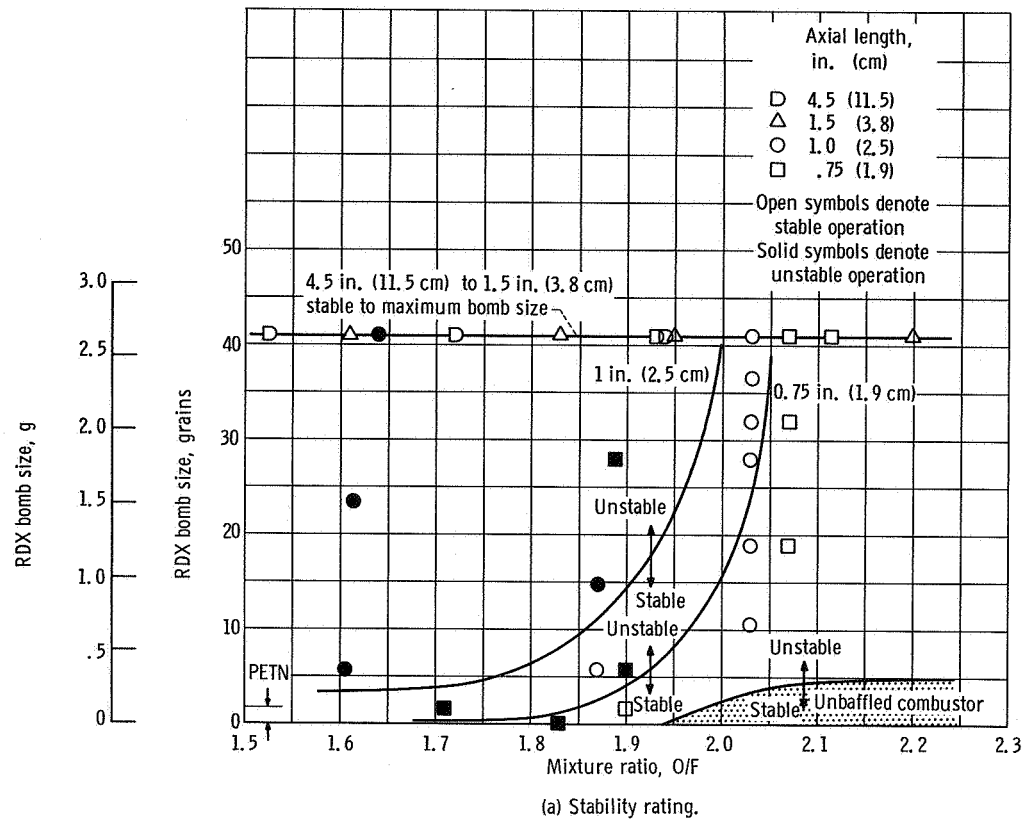
(b) Spectral density plot of instability. Mixture ratio, 1.55.

Figure 9. - Stability characteristics of the three-bladed baffle.



(c) Spectral density plot of instability induced while testing 1-inch (2.5-cm) blade length baffle. Mixture ratio, 1.86.

Figure 10. - Stability characteristics of four-bladed (unsymmetrical compartment) baffles.



(c) Spectral density plot of instability induced while testing the 3/4-inch (1.9 cm) blade length baffle. Mixture ratio, 1.89.

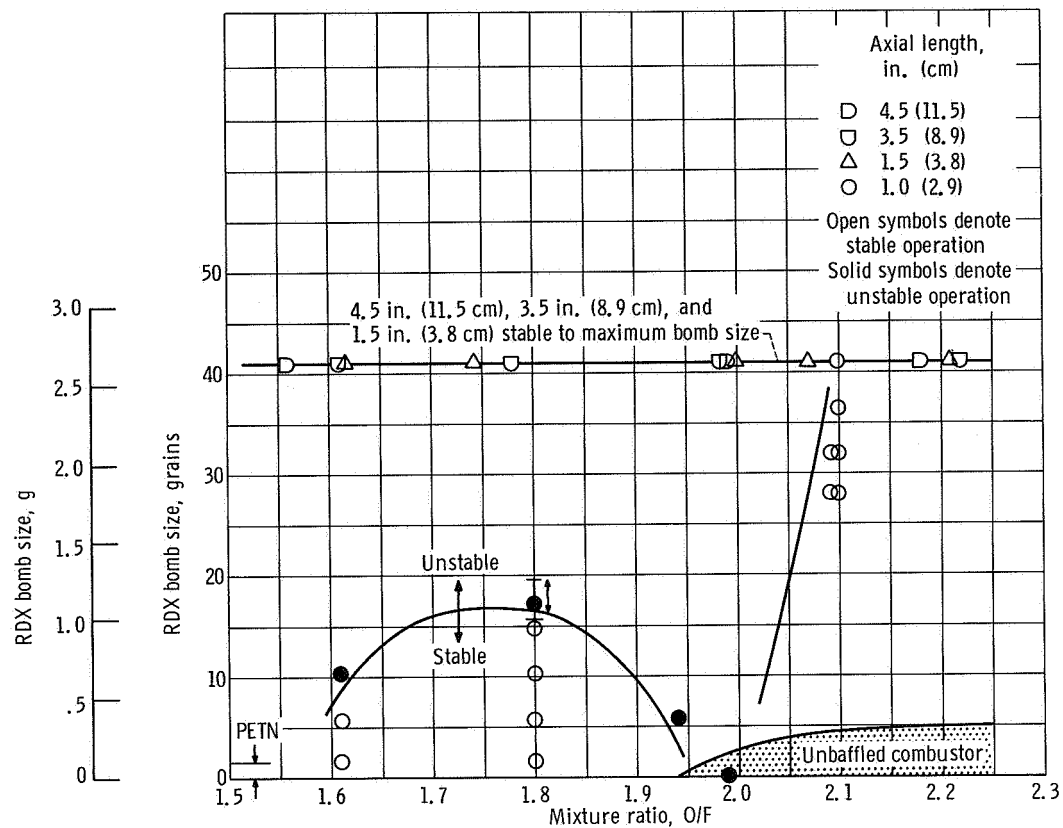
Figure 11. - Stability characteristics of five-bladed baffle of various axial lengths.

combustor (fig. 9(a)), even though complete stability was not provided. The screech mode induced was the first-radial mode (5000 Hz), as seen in the spectral density plot (fig. 9(b)). The baffle successfully damped the predominant first-tangential mode which had been present in the unbaffled injector (fig. 9(b)). It should be noted that a radial blade arrangement is not expected to be effective against a radial mode. The results indicate that instability is induced in the mode with least resistance. This is similar to the findings of the acoustic liner tests of reference 1 and baffle tests of reference 6.

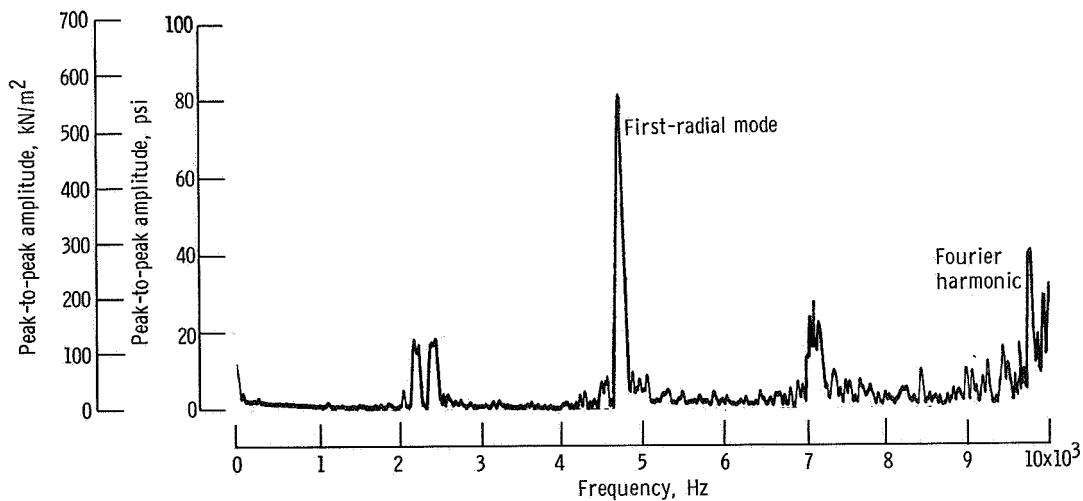
Three axial lengths were tested with the four-blade unsymmetrical compartment configuration (table I). The 4.5-inch (11.5-cm) baffle was stable at all mixture ratios up to the maximum charge size of 41 grains (2.66 g) (fig. 10(a)). The 1.5-inch (3.8-cm) long baffle was stable to all 41-grain (2.66-g) pulses except at a mixture ratio of 1.92 where 32 grains induced the first-radial mode (fig. 10(b)). With the 1.0-inch (2.5-cm) length, an average bomb size of about 2 grains (0.13 g) induced screech up to a mixture ratio of about 1.95. This blade length only slightly improved the stability of the unbaffled combustor. The screech mode was predominantly first radial with a first-tangential component also present (fig. 10(c)). Thus, for the four-bladed baffle, a critical blade length existed between 1.0 and 1.5 inch (2.5 and 3.8 cm) where a major change in stability was demonstrated.

The five-blade configuration was rated at 4.5-, 1.5-, 1.0-, and 0.75-inch (11.9-, 3.8-, 2.5-, and 1.9-cm) axial lengths, and the stability data are presented in figure 11(a). The 4.5- and 1.5-inch (11.5- and 3.8-cm) configurations were stable to the maximum charge size at all mixture ratios. The 1.0- and 0.75-inch (2.5- and 1.9-cm) configurations were pulsed unstable between $O/F = 1.6$ and 1.9. However, the 1.0-inch (2.5-cm) baffle was slightly more stable than the 0.75-inch (1.9-cm) baffle. Neither blade length configuration could be pulsed unstable above a mixture ratio of 2.0. The instability modes encountered (fig. 11(b)) were predominantly the first radial with the 1-inch (2.5-cm) long blades while those encountered with the 0.75-inch (1.9-cm) blades were first tangential (fig. 11(c)). Apparently as the baffle length was reduced, two stability zones were crossed: one between 1.5 inches (3.8 cm) and 1.0 inch (2.5 cm) where stability changed drastically as in the case of the four-bladed baffle and the other between 1.0 inch (2.5 cm) and 0.75 inch (1.9 cm) where the unbaffled chamber mode was encountered and the stability was only slightly improved over the unbaffled configuration.

The stability data are presented in figure 12(a) for the 10 bladed baffles. The axial lengths rated were 4.5, 3.5, 1.5, and 1.0 inch (11.5, 8.9, 3.8, and 2.5 cm), with all but the 1.0-inch (2.5-cm) baffle stable over the mixture ratio range up to the maximum charge size. The stability of the 1-inch (2.5-cm) configuration varied widely over the mixture ratio range studied. The stability varied from spontaneous instability to in excess of 15 grains (0.97 g) for mixture ratios from 1.6 to 2.0. No explanation has been found for the large variance in the stability. Note again, though, the large decrease in

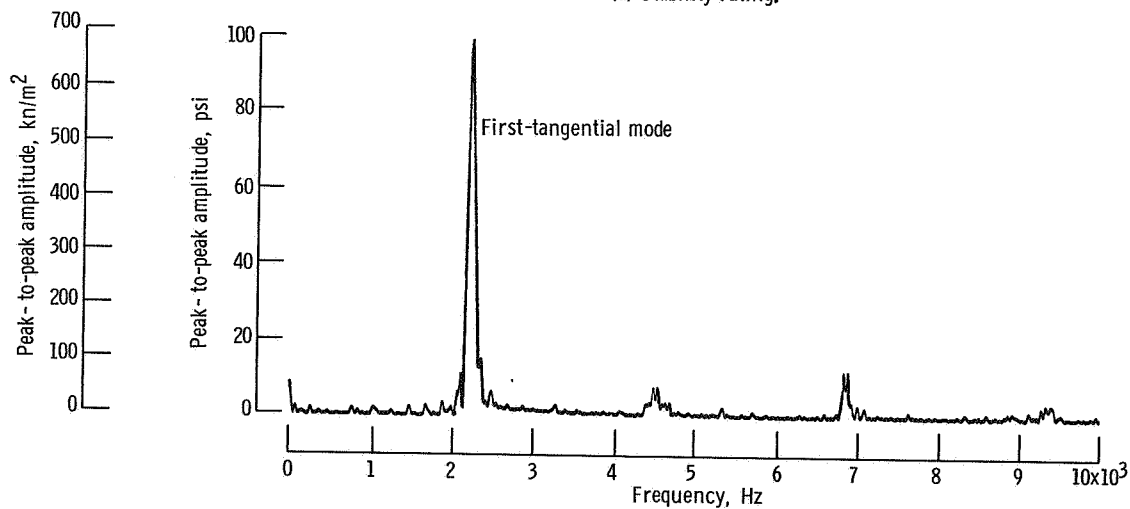
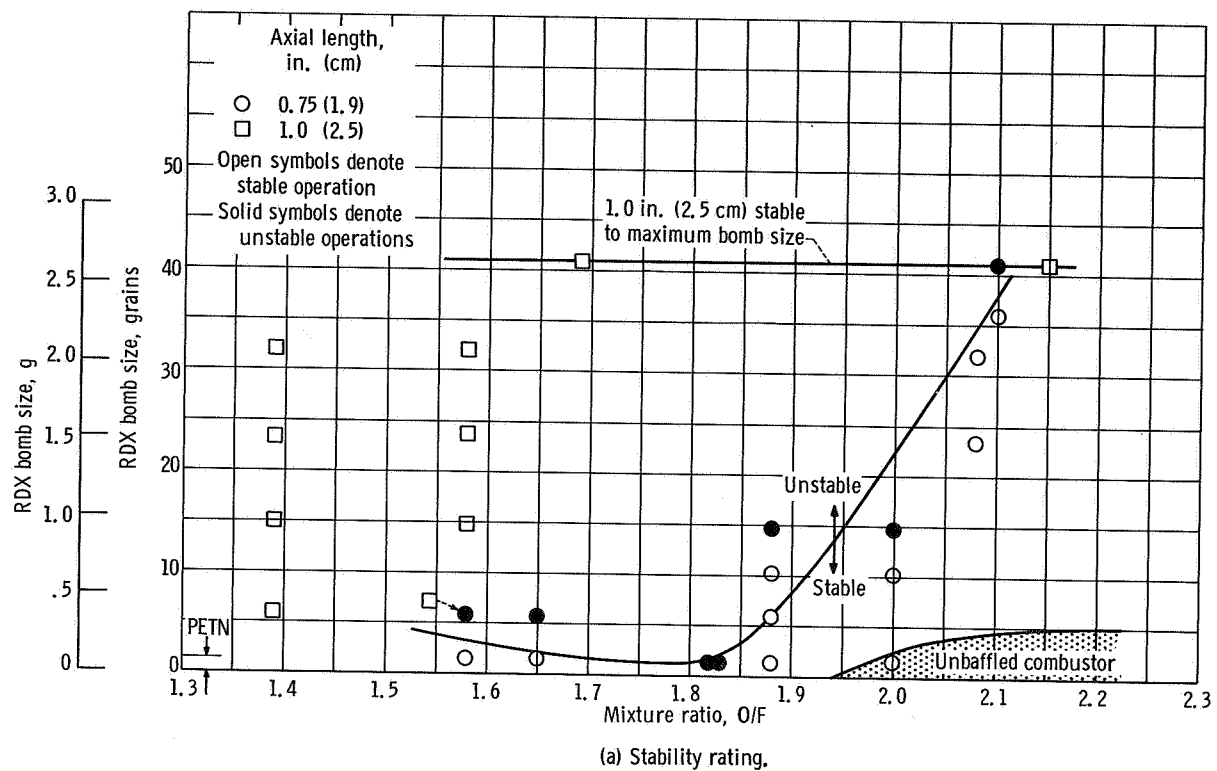


(a) Stability rating.



(b) Spectral density plot of instability induced while testing 1-inch (2.5-cm) blade length baffle. Mixture ratio, 1.94.

Figure 12. - Stability characteristics of 10-bladed baffle of various axial lengths.



(b) Spectral density plot of instability induced while testing 3/4-inch (1.9-cm) blade length baffle. Mixture ratio, 1.82.

Figure 13. - Stability characteristics of 20-compartment baffles.

stability between the 1.5-inch (3.8-cm) and 1.0-inch (2.5-cm) axial lengths. Also note that, at mixture ratios above 2.0, the 1-inch (2.5-cm) baffle could not be pulsed unstable. It can be seen from figure 12(b) that the predominant mode was again first radial.

The final configuration was a 20-compartment baffle which had 10 blades with a ring midway between the injector center and chamber wall (see table I). Axial lengths of 1.0 and 0.75 inch (2.5 and 1.9 cm) were stability rated and the data are presented in figure 13(a). As previously mentioned, the stability (of the 0.75-in. (1.9-cm) length) increased appreciably above a mixture ratio of 2.0. The 1-inch (2.5-cm) axial blade length was stable up to a maximum of 41 grains (2.66 g) but the 0.75-inch (1.9-cm) configuration was pulsed unstable in the first-tangential mode (fig. 13(b)). Two comparisons can be drawn from the results of this configuration. (1) In comparison with the 1-inch (2.5-cm) 10-bladed baffle, the addition of a ring (making 20 compartments with 1-in. (2.5-cm) axial length) increased the stability to 41 grains (2.66 g) (maximum). The ring would not permit a radial mode as in the case of the radially oriented blades of the 10-bladed baffle thus increasing stability. This leads to a conclusion that the largest (maximum) compartment dimension orientation is important with respect to the instability mode. (2) A comparison can be made with the 0.75-inch (1.9-cm), five-bladed configuration as to the mode; that is, the mode induced was first tangential for both the five-blade

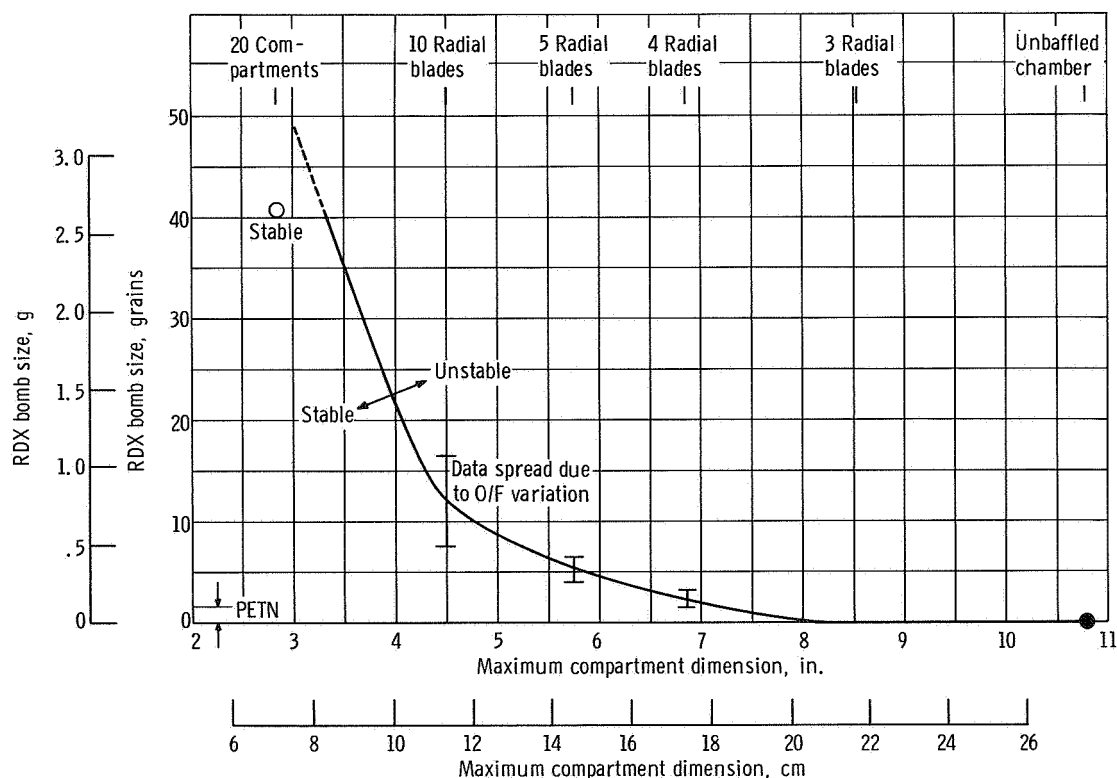


Figure 14. - Correlation of results for constant blade axial length of 1.0 inch (2.5 cm). Mixture ratio, 1.6 to 1.8 (using faired curves).

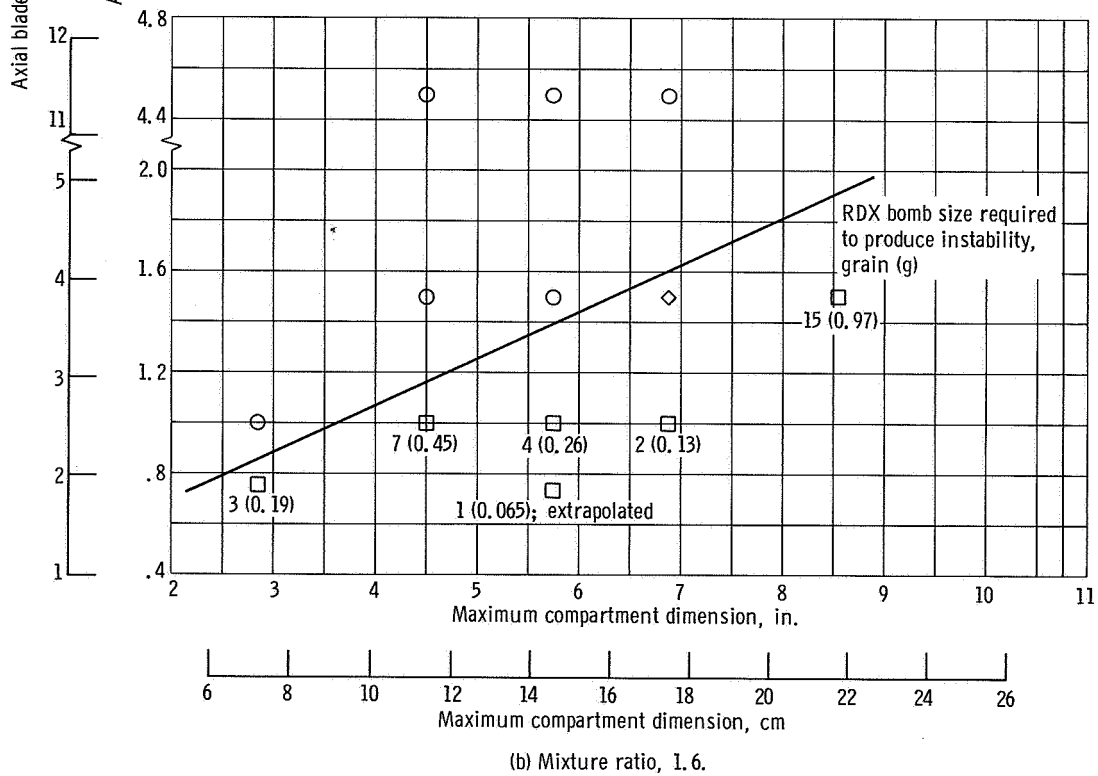
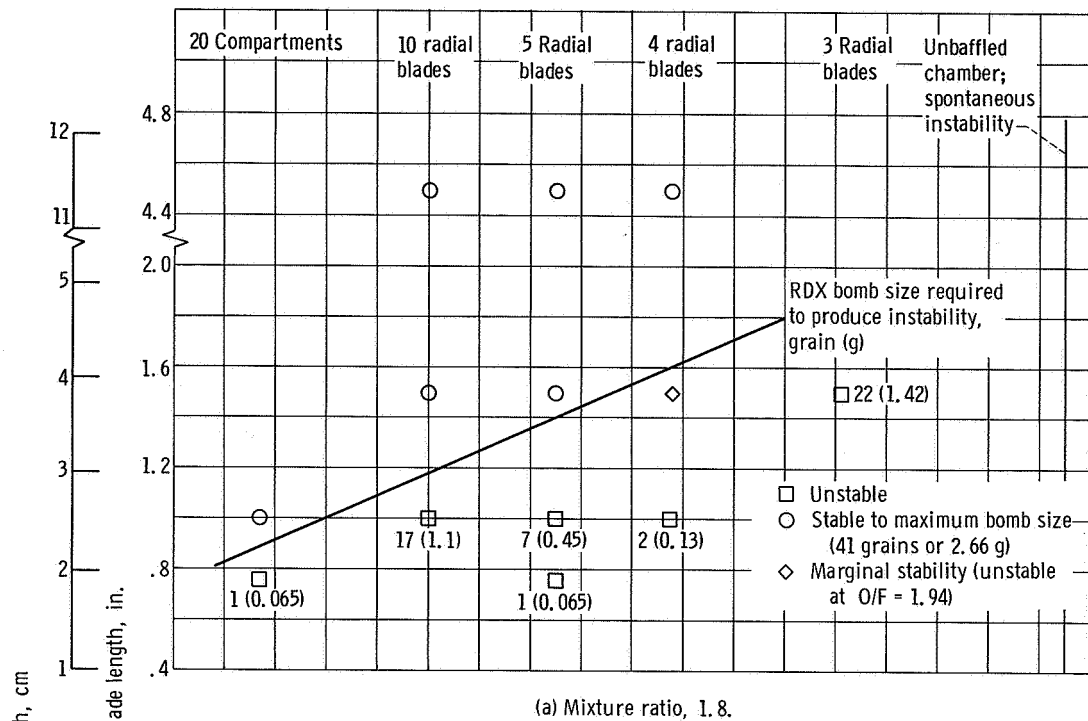


Figure 15. - Correlation of baffle results; cross plotted from faired curves.

and the 20-compartment, 0.75-inch (1.9-cm) baffles. Therefore, it also appears that increasing the number of compartments improved stability only slightly when blade axial length was less than 0.75 inch (1.9 cm). In summarizing all the baffle testing data discussed below a mixture ratio of about 2.0, a critical length for stability was between 1.0 and 1.5 inches (2.5 and 3.8 cm). Above a mixture ratio of 2.0, it was apparently below 0.75 inch (1.9 cm) but the chugging encountered in this mixture ratio range makes the conclusion uncertain.

All the configurations rated at 1-inch (2.5-cm) axial length are summarized in figure 14. Data are plotted as a function of maximum compartment dimension over a range of mixture ratios from 1.6 to 1.8. The data above 1.8 are not presented, although stability was maximum, because of the uncertainty created by the chugging encountered in this range. Maximum compartment dimension is defined as the largest compartment dimension when all compartments are identical. When compartments vary in size, it is the average of the maximum dimension of each compartment. As can be seen in the figure, baffles increased the stability of the combustor as the number of compartments increased or as the maximum compartment dimension decreased.

A correlation of blade axial length to maximum compartment dimension (fig. 15) was quite similar regardless of mixture ratio even though required bomb sizes varied. As the compartment dimension is decreased, the blade length required for stable combustion up to 41 grains (2.66 g) also is reduced. A baffle with a 1-inch (2.5-cm) blade length would be stable up to 41 grains (2.66 g) if the maximum compartment dimension was kept less than 3.5 inches (8.9 cm). The results found using storable propellants (fig. 15) were remarkably similar to those found using the hydrogen-oxygen combination (fig. 16 from ref. 3) even though the thrust level, thrust per element, and rating techniques were different. A comparison of the figures shows a linear relation between maximum compartment dimension and axial blade length with about the same slope. The hydrogen-oxygen stability (fig. 16) improves (i.e., shorter baffle axial lengths are required) down to a maximum compartment dimension of about 3.5 inches (8.9 cm). At maximum compartment dimensions less than 3.5 inches (8.9 cm), a 1-inch (2.5-cm) axial length is required for stability.

The various baffles (storables) had no noticeable effect on the characteristic exhaust velocity C^* efficiency as shown in figure 17. Only unbaffled combustor data above a mixture ratio of about 1.9 is presented for comparison because the combustor was spontaneously unstable below 1.9.

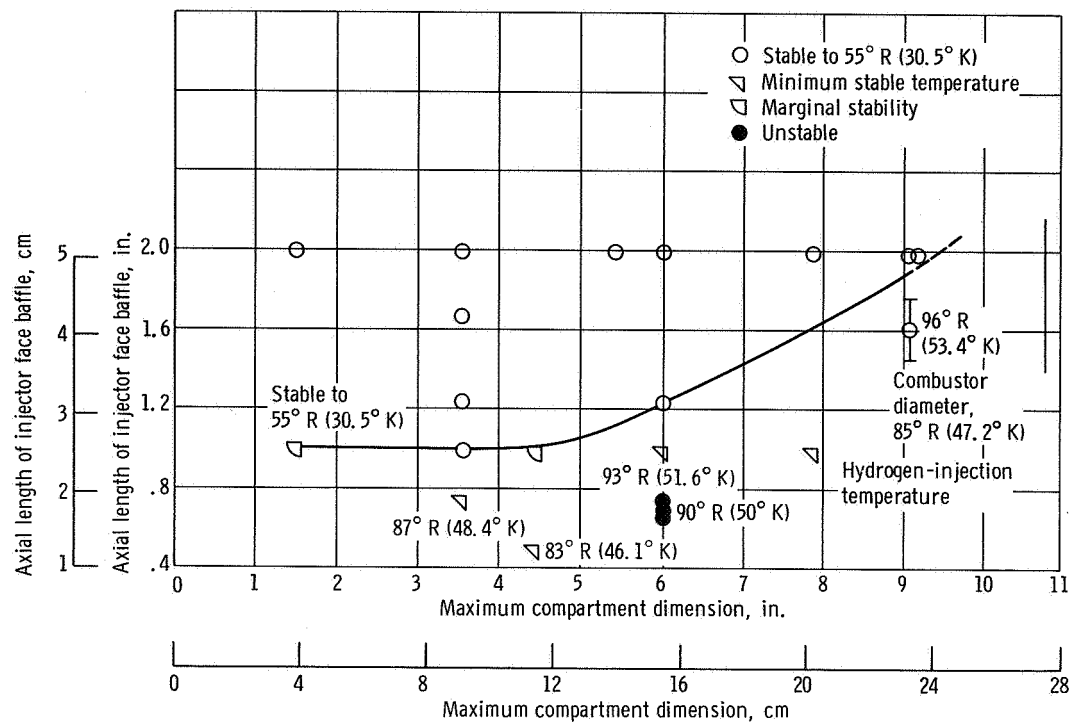


Figure 16. - Relation of baffle length and maximum compartment dimension to stability for hydrogen - oxygen propellants (ref. 3). Mixture ratio, 5.0.

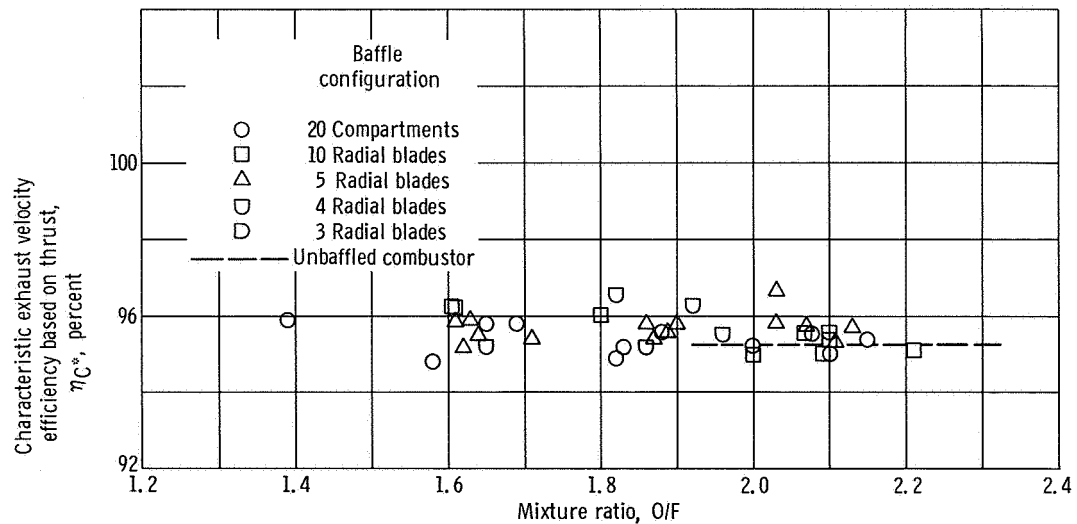


Figure 17. - Stable combustion performance for all baffle configurations and unbaffled combustor.

Concentrated Injection Distribution with Divergent Chamber Geometry Effects

According to the analytical model described by Priem in reference 13, an increased velocity differential between the propellant droplets and the combustion gas should have a favorable influence on stability. The theory of reference 13 shows that larger disturbances should be needed to initiate instability with increased velocity difference. By modifying the injector size and the combustor shape, high differential velocities can be achieved in the sensitive combustion area near the injector. This type combustor then should have favorable tangential-mode stability. Accordingly, tests were conducted using a 5.5-inch (14-cm) diameter, 50-element, triplet-injector as presented in figure 3. Three chamber shapes were tested with the injector (fig. 3): a 10.8-inch (27.4-cm) diameter cylinder, a 15° taper, and a 30° taper. The bomb ring was located 10 inches (25.4 cm) downstream from the injector in all tests.

Stability results of the concentrated injection study are presented in figure 18(a). The 10-inch (25.4-cm) cylindrical chamber was pulsed unstable at a mixture ratio of 2.0 with 41 grains (2.66 g) of RDX and at 2.2 with 23 grains (1.49 g). The predominant mode corresponded to first tangential, as seen in figure 18(c), which was rather unexpected because of the injector concentration at the center of the combustor. The 10-inch (25.4-cm) long, 15° tapered section was then substituted for the 10-inch (25.4-cm) cylindrical section, and it was completely stable when pulsed with bombs up to 41 grains over a nominal range of mixture ratios from 1.60 to 2.20 (fig. 18(a)). However, the 5-inch (12.7-cm) long, 30° taper with the 5-inch (12.7-cm) cylindrical section was spontaneously unstable at mixture ratios from 1.5 to 1.7. The screech frequency was predominantly at 2400 hertz (first-tangential mode for diameter of 10.8 in. (27.4 cm)) with a 4800-hertz harmonic at a slightly lower amplitude (fig. 18(d)). A comparison of the wave shapes at three positions in the chamber revealed that the mode was standing. This explained the high-amplitude harmonic at 4800 hertz. At a mixture ratio of 1.7, 36.5 grains (2.47 g) of explosive damped the oscillations which had initiated spontaneously. No instability could be induced at mixture ratios from 1.8 to 2.2 with the 41-grain (2.66-g) maximum charge.

Therefore, the cylindrical and 30° tapered chambers were less stable than the 15° tapered chamber even though the instability occurred at widely separated mixture ratios. The data tended to follow the theory (ref. 13) which predicted that a higher velocity differential, such as obtained with the 15° tapered chamber, has a greater resistance to instability. The effects of possible recirculation of combustion gases in these chamber configurations on the actual velocity differential is unknown.

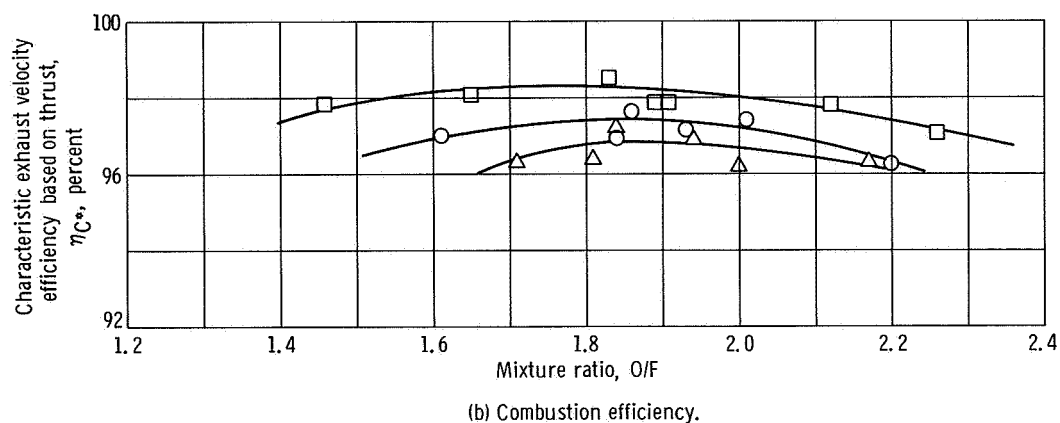
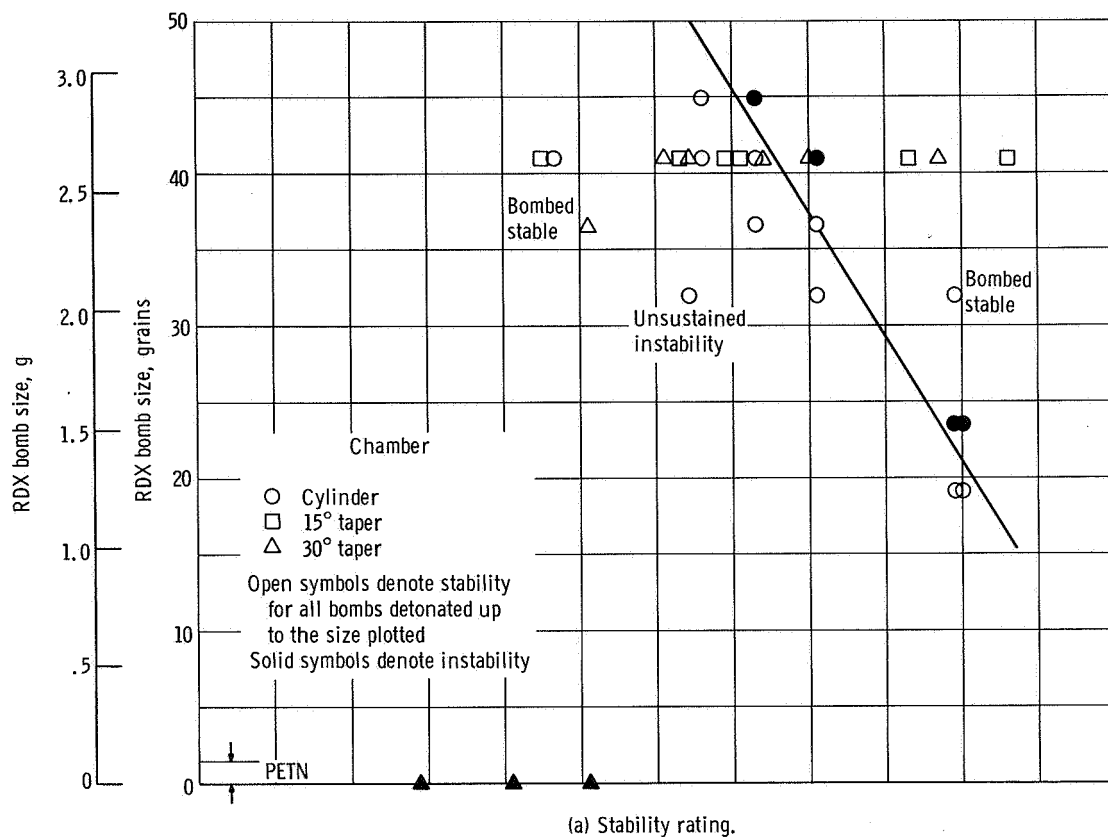


Figure 18. - Injection concentration effects on stability and performance using storable propellants.

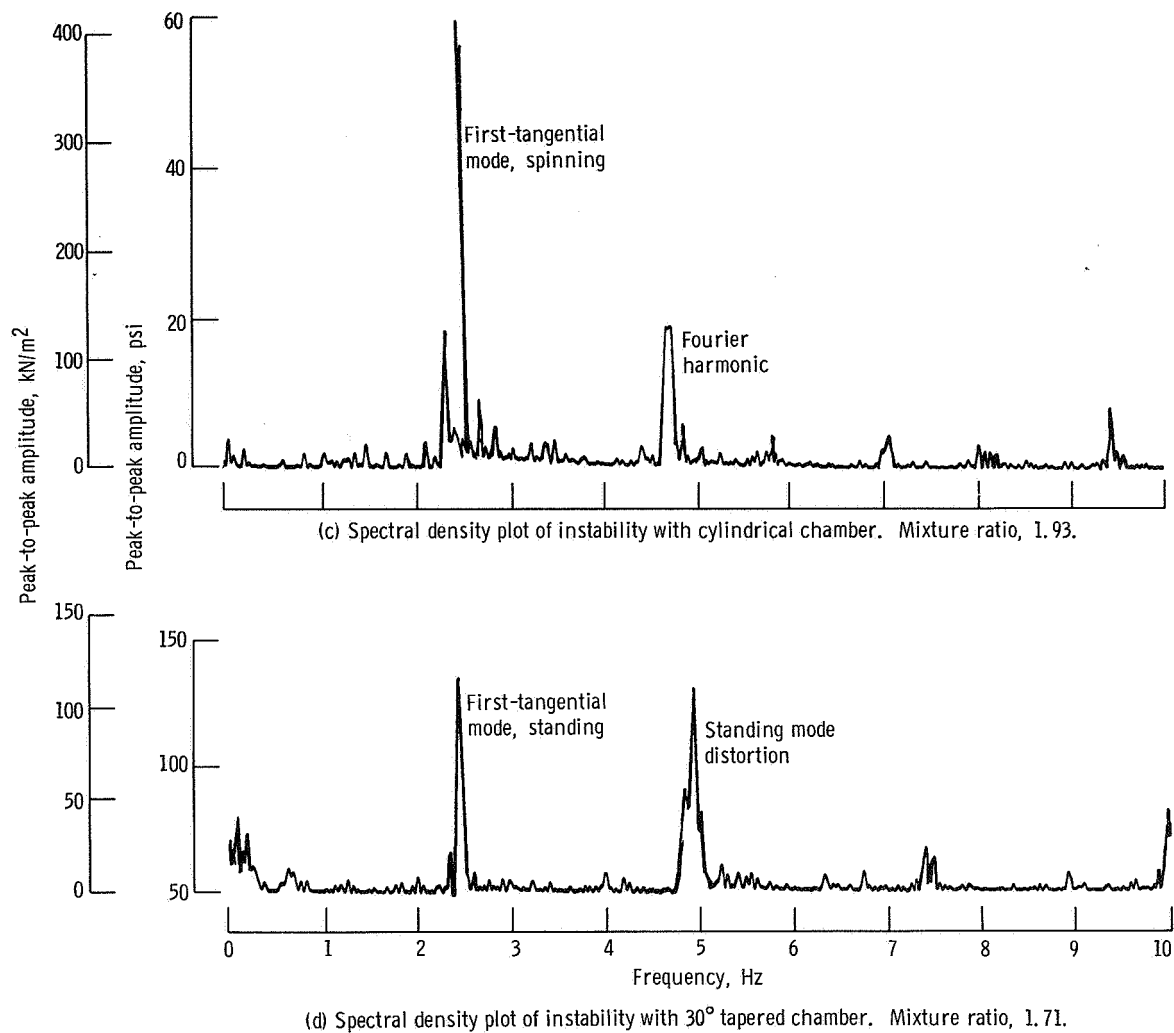


Figure 18. - Concluded.

Hydrogen-oxygen data from reference 4 which are presented in figure 19 indicate decreased stability as the taper angle decreased but the instability occurred in a longitudinal mode. Therefore, a problem arises in comparing this with either the storable tests or the theoretical analysis which did not consider a longitudinal mode.

The C^* efficiency of the three chamber shapes is presented in figure 18(b). Propellant mixing and hence efficiency were probably affected by complex recirculation zones created by the various chamber geometries. The 15° tapered chamber exhibited the highest efficiency, and apparently this taper angle reduced the recirculation, which resulted in more complete combustion. The other configurations may have allowed recirculation which detrimentally affected the mixing and combustion processes.

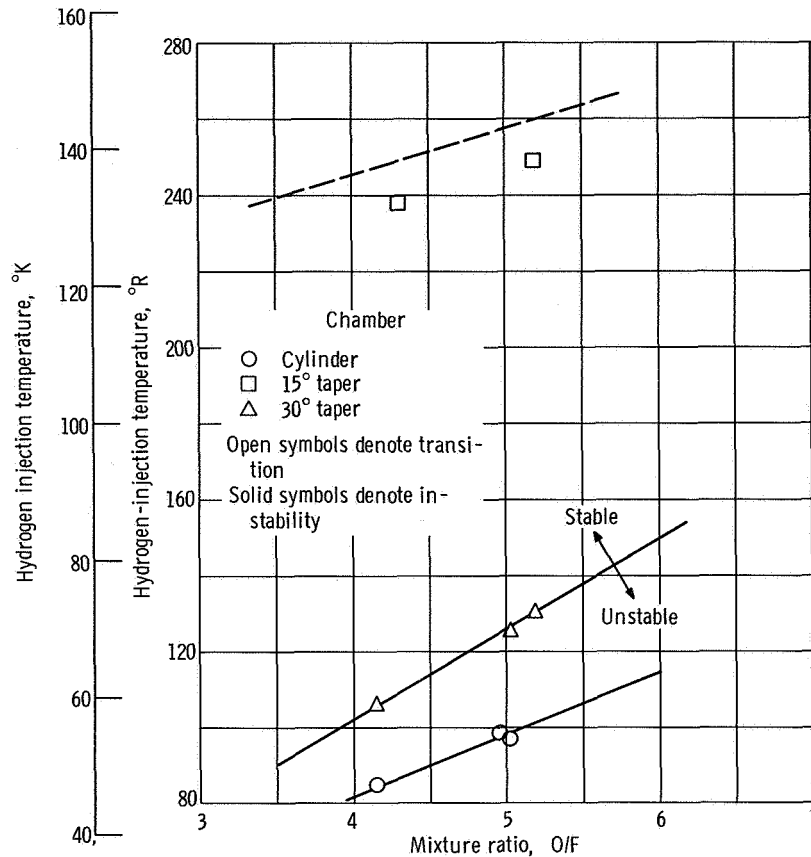


Figure 19. - Effect of injector pattern concentration on stability using hydrogen-oxygen propellants (ref. 4).

Nozzle Entrance Length Effect

An analytical investigation in reference 14 was made to determine the effect of the subsonic length of the nozzle (i.e., the length of converging section) on longitudinal- and tangential-mode combustion instability. The effect on longitudinal-mode instability had been analyzed previously by Crocco. His findings showed that, by spreading the velocity distribution, the wave reflections would be dispersed, hence the probability of longitudinal instability is reduced. Using Crocco's theory, it was shown in reference 14 that increasing the nozzle entrance length improved longitudinal stability by raising the pressure-interaction index for the longitudinal modes (i.e., the instability zone is moved away from the operating point). But, the calculations made in reference 14 also showed a destabilizing effect of increasing nozzle length on the first-tangential mode (i.e., the pressure-interaction index was moved closer to the operating point for the tangential mode). Therefore, the tests reported herein were designed to investigate the nozzle entrance shape effects in an actual rocket for comparison with the theoretical predictions.

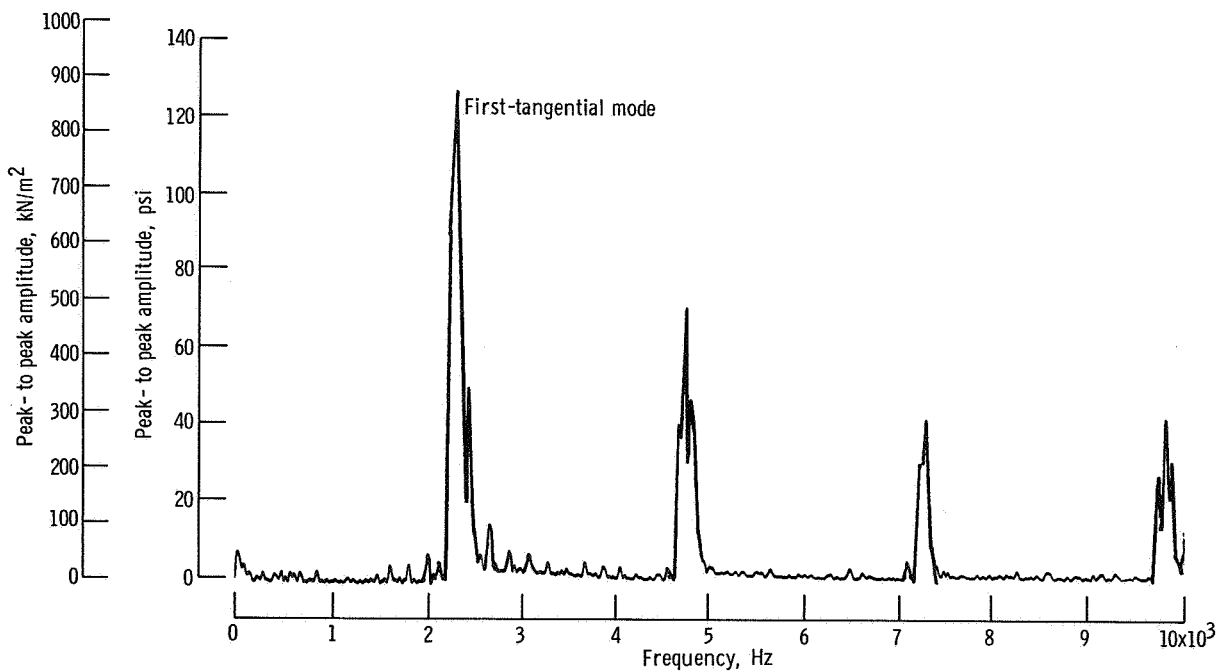
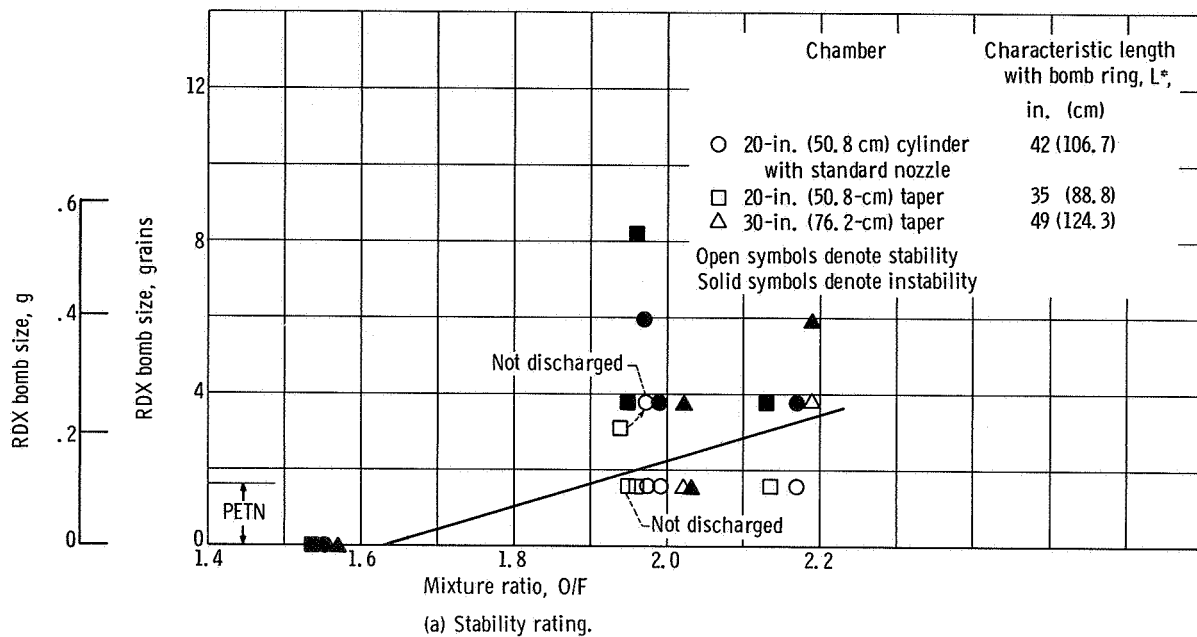


Figure 20. - Nozzle entrance length effects on stability using 90-element injector with storable propellants.

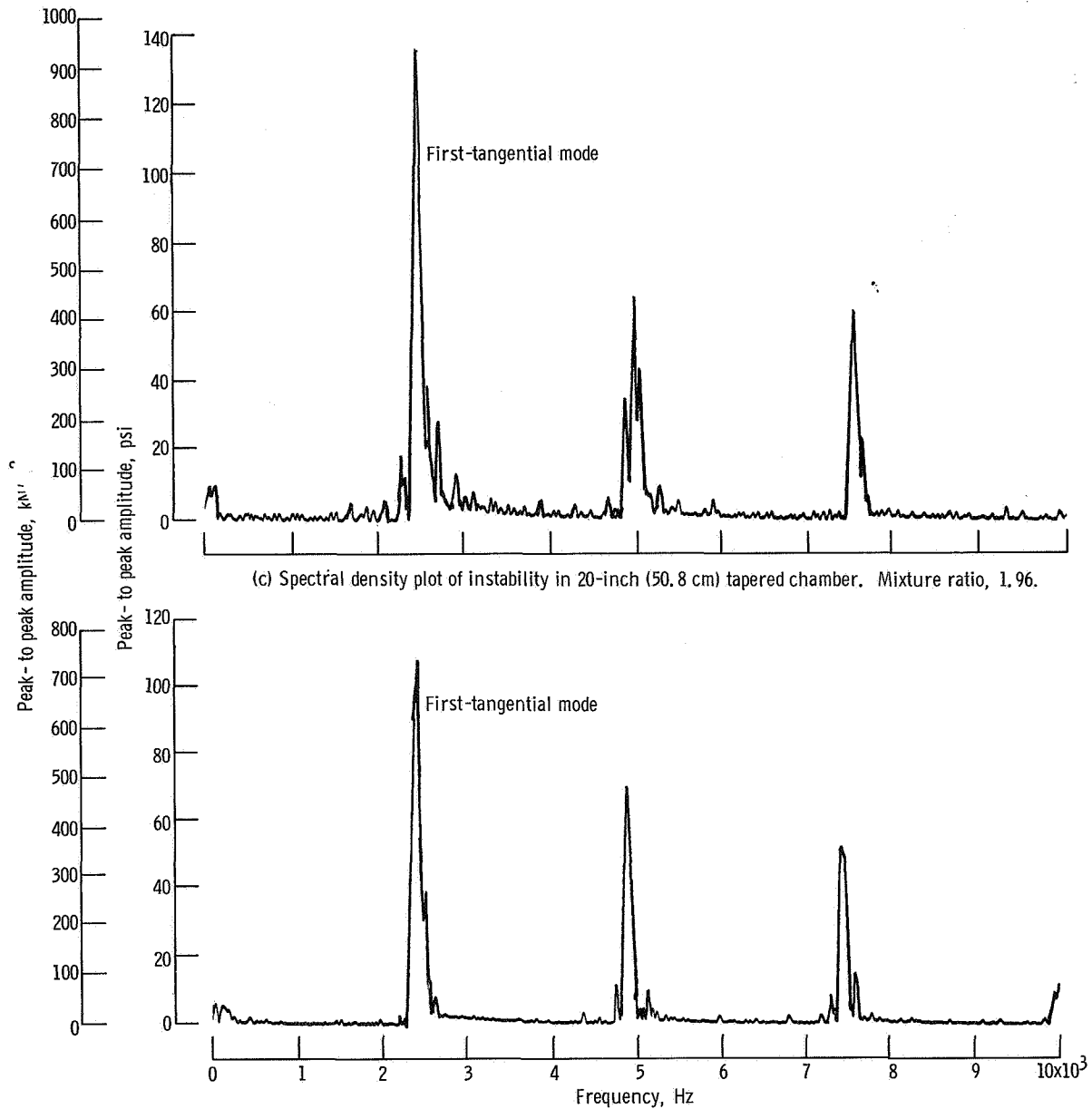
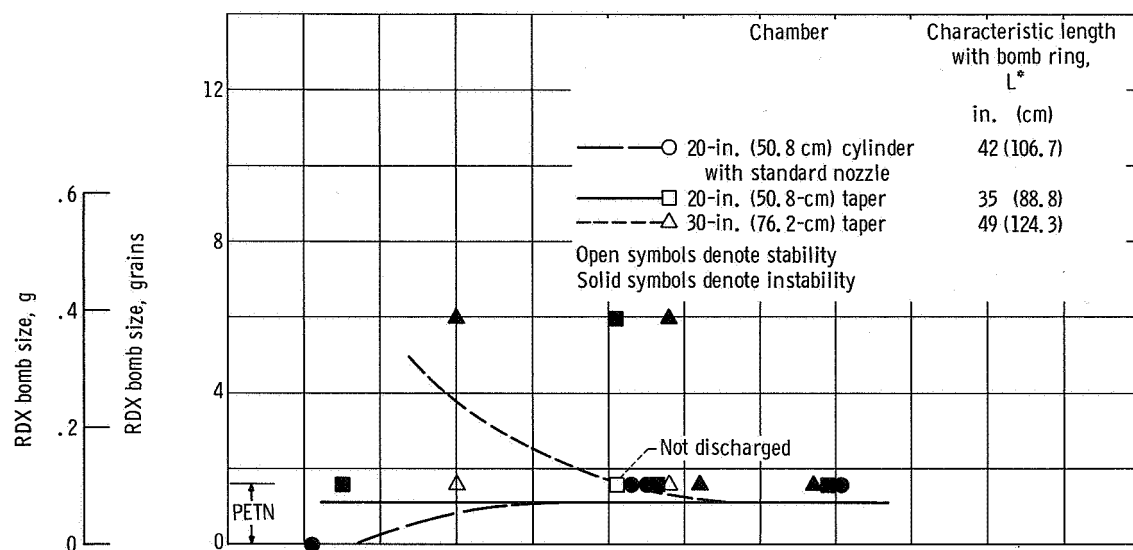
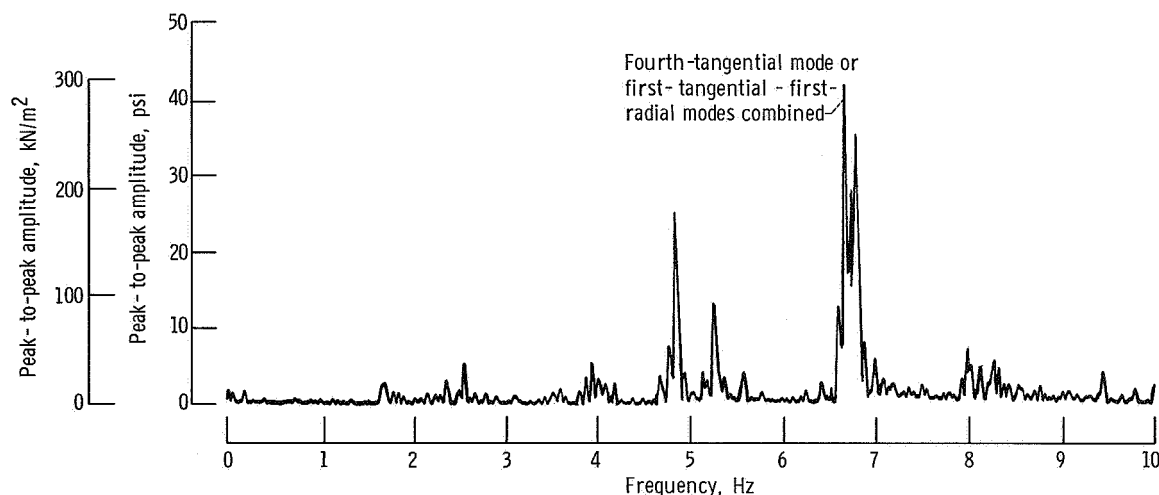


Figure 20. - Concluded.

Tapered chambers of 20- and 30-inch (50.8- and 76.2-cm) lengths (excluding bomb ring) (fig. 4(c)) were tested with two injectors with 90 and 401 elements (figs. 4(a) and (b)). A cylindrical chamber (20 in. (50.9 cm) excluding bomb ring) with a standard curved-entrance nozzle 5.7 inches (14.5 cm) long was used as a baseline. A stability map of the three chamber designs which used a 90-element injector is presented in figure 20(a). In general, stability increased with increasing mixture ratio, but no appreciable stability difference was found between the three chamber configurations. Typical spectral density plots are presented in figures 20(b) to (d) for the three configurations.



(a) Stability rating.



(b) Spectral density plot of screech in cylindrical chamber. Mixture ratio, 1.95.

Figure 21. - Nozzle entrance length effects on stability using 401-element injector with storable propel-

In all cases, the first-tangential mode was predominant with Fourier harmonics shown at multiples produced by the spectral analyzer.

When tested with the 401-element injector at mixture ratios from 2.0 to 2.2, the stability margin of the three combustors was the same with about 1.8 grains (0.12 g) required to induce instability (fig. 21(a)). However, the stability is slightly different in the mixture ratio range near 1.6. The cylindrical chamber was spontaneously unstable while the tapered chambers required pulsing. The 30-inch (76.2-cm) taper chamber was slightly more stable than the others and required 6 grains (0.39 g) of RDX to induce instability. A possible explanation is that the tangential-mode instability is initiated by a longitudinal disturbance whether by bombing or spontaneous initiation (longitudinal-mode

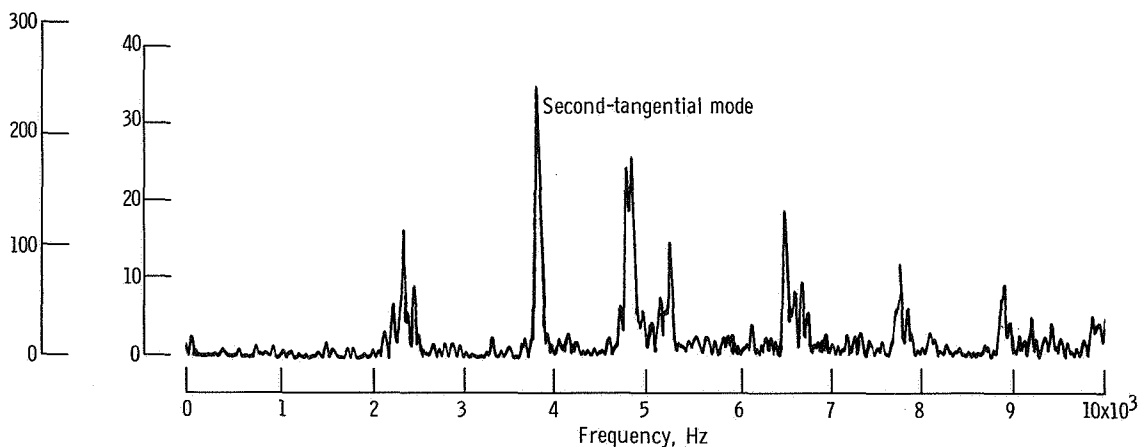
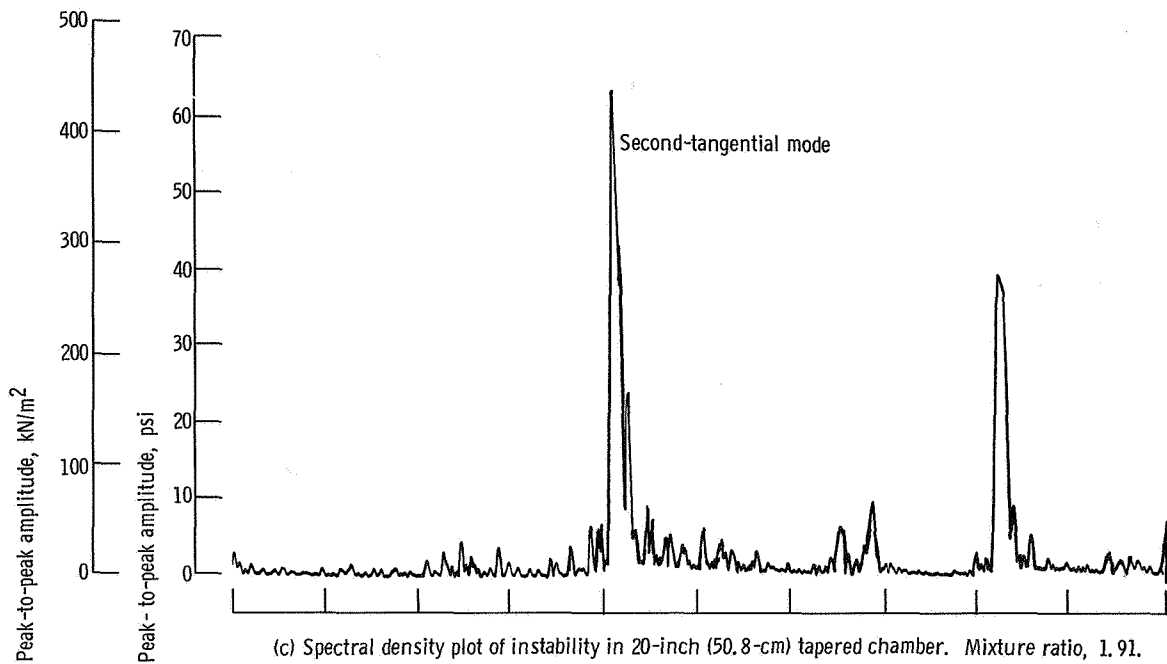
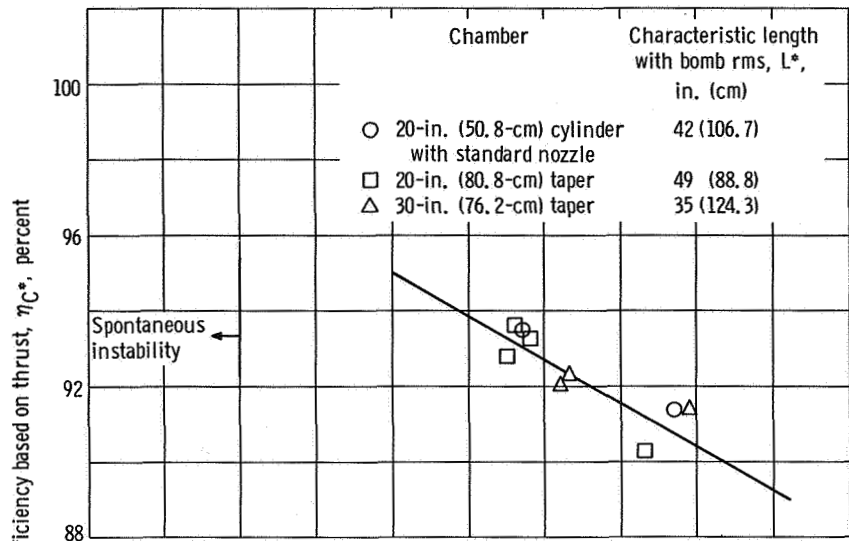
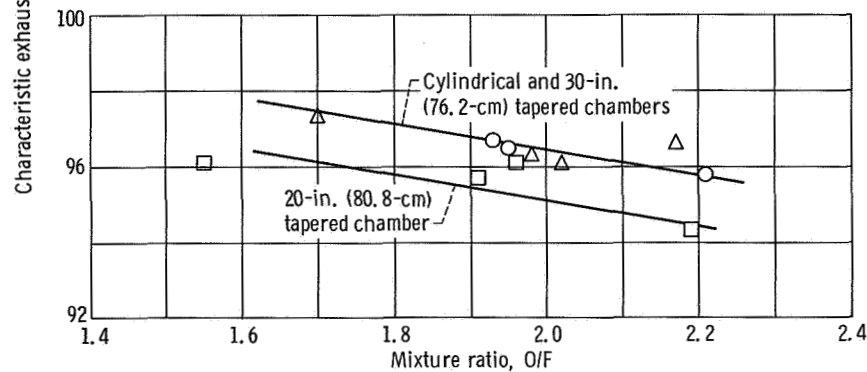


Figure 21. - Concluded.

stability increased with increased nozzle entrance length, while tangential-mode stability decreased). Although a more detailed analysis is necessary, this could be a possible explanation of the increasing overall stability at a mixture ratio of 1.6 with increasing nozzle entrance length. This argument would, however, depend on the location of the operating point with respect to the Crocco theoretical stability boundaries for the two modes. The instability induced in the cylindrical chamber (fig. 21(b)) was predominantly the fourth-tangential mode or the combined first-tangential - first-radial modes (about 6700 Hz); whereas, in the cases of the 20- and 30-inch (50.7- and 76.2-cm) tapered chambers (figs. 21(c) and (d)), the second-tangential mode (4000 Hz) was predominant.



(a) 90-Element injector.



(b) 401-Element injector.

Figure 22. - Nozzle entrance length effects on characteristic exhaust velocity efficiency.

In any case, the data obtained were not sufficient to delineate nozzle length effects. It appears that increasing nozzle entrance length has little value as a screech suppressant.

The C^* efficiency was not affected by the chamber geometry when tested with the 90-element injector (fig. 22(a)). With the 401-element injector, the cylindrical and 30-inch (76.2-cm) combustors displayed slightly higher efficiency than the 20-inch (50.8-cm) combustor (fig. 22(b)). This was probably due to the shorter characteristic length (L^*) of the 20-inch (50.8-cm) configuration at this contraction ratio (1.9).

Injector Element Radial Coverage Effect

Radial distribution of injector elements on the injector faceplate had a significant effect on combustion instability during the hydrogen-oxygen screech program (ref. 5). The width of the gap or void between the outer row of elements and the chamber wall seemed to be the controlling factor; that is, decreasing radial coverage of the injector-element pattern or increasing the void tended to be destabilizing from 100 to about 85 percent coverage. (Percent coverage was defined as the effective injection distribution area divided by the chamber cross sectional area, when uniform distribution across the injector is assumed. See fig. 5.) The stability increased slightly from 72 to 60 percent for the first-transverse mode, but the first-radial mode also appeared at 60 percent coverage. Similar tests were made using storable propellants to investigate this variable.

Tests were conducted using the same 401-element injector as used in the nozzle entrance length study (fig. 4(a)). The outer row of elements was welded closed, however, thereby reducing the number of elements to 333. The original injector had an 87-percent element coverage and the modified injector was 73 percent. Closing the elements does affect thrust per element, but raising the thrust per element has been shown to be stabilizing in reference 8.

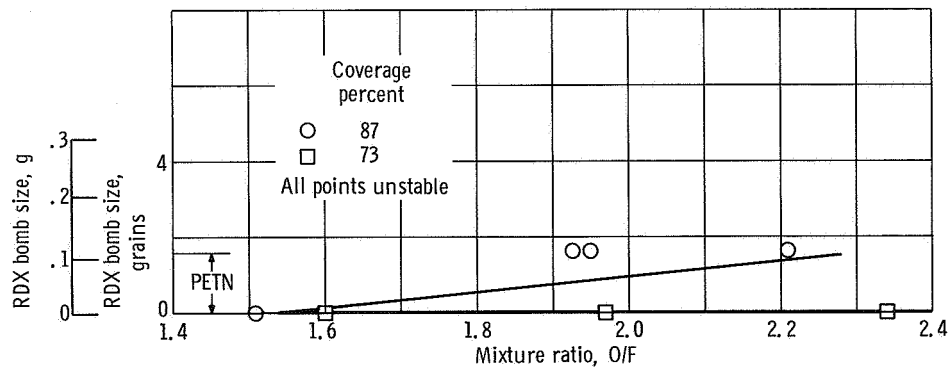


Figure 23. - Stability effects of injector face element radial coverage (peripheral gap height) using storable propellants. Stability increases with increasing bomb size.

Results of these tests, as presented in figure 23(a), illustrate that stability decreased slightly with decreasing percent coverage or as the peripheral gas was enlarged. The 87-percent coverage injector required a charge of about 1.6 grains (0.104 g) to induce instability at mixture ratios greater than 1.93, whereas the 73-percent injector was spontaneously unstable over the mixture ratio range tested, even though the thrust-per-element was increased somewhat.

The result is similar but less pronounced than the hydrogen-oxygen results (fig. 24). The hydrogen-oxygen study was made by testing various injectors with the same injection

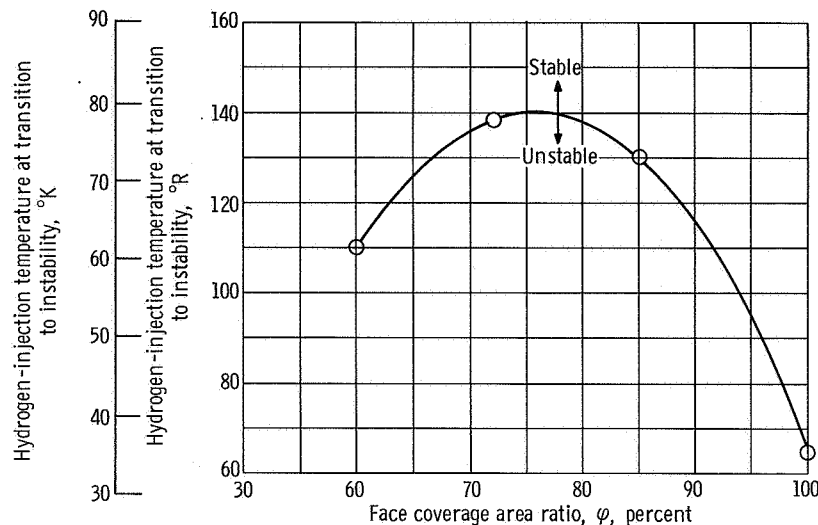


Figure 24. - Stability effects of injector face element radial coverage using hydrogen-oxygen propellants (ref. 5).

areas and equal numbers of elements. The coverage was varied by rearranging the elements. However, one test was made by welding the outer row of elements closed. The results of this test showed an increase in hydrogen-injection temperature (decreased stability) of 50°R (28°K). In the storable-propellant study, elements were similarly closed with propellant mass flow kept constant. This would increase the injection velocities which would, in the storable-propellant case, affect the jet breakup, vaporization, and combustion of the propellants. The void would probably also create a recirculation zone at the combustor wall, which could have a detrimental effect on stability, so the effect here may be something other than face coverage.

SUMMARY OF RESULTS

The information in this report represents the results of a broad program to investigate the causes and cures of combustion instability. The most important results are as follows:

1. Injector face baffles were very successful in suppressing combustion instability in a rocket combustor using earth-storable propellants. A critical blade-axial length was found between 1.0 and 1.5 inches (2.5 and 3.8 cm) where a large change in stability occurred. Also, a correlation of blade length and maximum compartment dimension was found.
2. Increasing the velocity differential between the injectants and the combustion gases increased the tangential stability.

3. No significant effect on longitudinal- or tangential-mode instabilities was noted by increasing the nozzle entrance length.

4. A slight destabilizing effect was found when an element void was created at the circumference of the injector by closing elements.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, January 17, 1968,

128-21-06-05-22.

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